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SECTION 26

ILLUMINATION*

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26.1 RADIANT ENERGY AND LIGHT

For the principal purposes of illumination design, light is defined as visually evaluated radiant energy. The visible energy radiated by light source is found in a narrow band in the electromagnetic spectrum (Fig 26-1) approximately from 380 to 770 nanometers (nm). By extension, the art and science of illumination also include the applications of ultraviolet and infrared radiation. The principles of measurement, methods of control, and fundamentals of lighting system and equipment design in these fields are closely parallel to those long established in lighting practice.

26.2 QUANTITIES, UNITS, AND CONVERSION FACTORS¹

Luminous Flux. This is the time rate of flow of light. See Table 26-1. Radiant energy in the visible region of the spectrum varies in its ability to produce visual sensation, the variation depending upon

¹Includes some material from previous editions by Jack F. Parsons, Walter Sturrock, Karl A. Staley, John A. Kaufman, and Charles Amick.

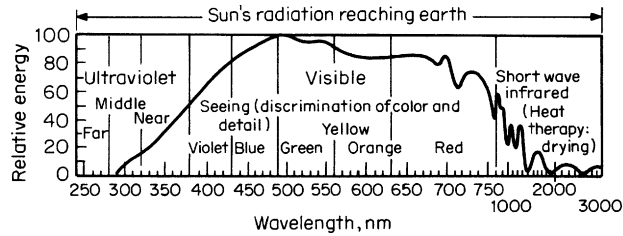


FIGURE 26-1 Ultraviolet, visible, and shortwave infrared are the three principal bands of the electromagnetic spectrum with which illuminating engineering is concerned.

the wavelength. The ratio of the luminous flux to the corresponding radiant flux is known as spectral luminous efficacy and is expressed in lumens per watt (lm/W). This varies with wavelength, having a maximum at approximately 555 nm. The data are plotted in Fig. 26-2. At very low levels of illumination the position of the maximum sensitivity gradually shifts to 510 nm as a result of greater use of rod vision.

From the foregoing it is apparent that two sources may radiate equal amounts of energy in the visible region of the spectrum but have different amounts of luminous flux emitted, depending on the spectral distribution of the energy. The luminous flux (ϕ) is the integrated product of the energy per unit wavelength emitted by the source $P(\lambda)$, referred to as the source's spectral power distribution, and the spectral luminous efficacy $V(\lambda)$ as follows:

$$\phi = 683 \int_{\lambda=360}^{800} P(\lambda)V(\lambda)d\lambda$$

The lumen is the unit of luminous flux. Light sources (i.e., lamps) are rated in lumens.

Luminous Intensity. This is the luminous flux per unit solid angle in a specific direction. Hence, it is the luminous flux on a small surface normal to that direction, divided by the solid angle (in steradians) that the surface subtends at the source (see Table 26-1). The definition of luminous

TABLE 26-1 Standard Units, Symbols; and Defining Equations for Fundamental Photometric Quantities

Quantity*	Symbol	Defining equation	Unit	Symbolic abbreviation
Luminous flux	ϕ	$\Phi = dQ/dt$	lumen	lm
Illuminance (illumination)	E	$E = d\phi/dA$	footcandle (lumen per Φ square foot) lux (lm/m ²)	fc lx
Luminous existance	M	$M = d\Phi/dA$	lumen per square foot	lm/ft ²
Luminous intensity (candlepower)	I	$I = d\Phi/d\omega$ (ω = solid angle through which flux from point source is radiated)	candela (lumen per steradian)	cd
Luminance (photometric brightness)	L	$L = d^2\Phi/d(dA \cos \theta)$ $= dI/(dA \cos \theta)$ (θ = angle between line of sight and normal to surface considered)	candela per unit area cd/ft ² nit (cd/m ²) footlambert (cd/πft ²) [†]	ω etc. cd/ft ² fL
Luminous efficacy	K	$K = \Phi_i/\Phi_p$	lumen per watt	lm/W

*Quantities may be restricted to a narrow wavelength band by adding the word *spectral* and indicating the wavelength. The corresponding symbols are changed by adding a subscript λ , e.g., Q_λ , for a spectral concentration or a λ in parentheses, e.g., $K(\lambda)$, for a function of wavelength.

[†]The use of this unit is deprecated.

intensity applies strictly to a point light source. In practice, however, light emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed may be considered as coming from a point.

Candlepower is another term for luminous intensity, since the candela is the unit of luminous intensity. One candela is defined as the luminous intensity of $1/600,000$ m² of projected area of blackbody radiator operating at the temperature of solidification of platinum under a pressure of 101,325 Pa. It is also the luminous intensity when one lumen is directed within one steradian of solid angle. A steradian is a unit area on a sphere of radius one, thus there are 12.57 (4π) steradians surrounding any light source. The original definition of luminous intensity was in terms of the strength of a flame source, a standard candle.

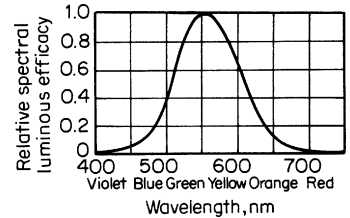


FIGURE 26-2 Spectral luminous efficacy, $V(\lambda)$, for normal human color vision.

Illuminance. This is the density of the luminous flux incident on a surface; it is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated. The term illumination is used to designate the act of illuminating or the state of being illuminated. Usually the context will indicate which meaning is intended, but the expression “level of illumination” is a term used to mean illuminance and should be discouraged.

Lux is the unit of illuminance when the meter is taken as the unit of length. It is the illumination on a surface 1 m^2 in area on which there is a uniformly distributed flux of 1 lm , or the illumination produced on a surface, all points of which are at a distance of 1 m from a directionally uniform point source of one candela.

Footcandle is the inch-pound system unit of illuminance where the foot is taken as the unit of length. See Table 26-2 for conversion factors between SI and inch-pound lighting units. Most conversions, like illuminance, involve a 10.76 factor since there are $10.76 \text{ ft}^2/\text{m}^2$ (e.g., $1 \text{ footcandle} = 10.76 \text{ lux}$).

Luminous Exitance. This is the density of luminous flux leaving a surface; it is the quotient of the luminous flux leaving the surface by the area of the surface. It applies to the aggregate flux that is emitted, reflected, or transmitted from the surface and is a nondirectional quantity.

Luminance. This is the quotient of the luminous flux leaving or arriving at an element of a surface and propagated in direction defined by an elementary cone containing the given direction, by the

TABLE 26-2 Conversion Factors for Lighting Units

A. Illuminance			
1 footcandle = 1 lumen per square foot		1 lux = 1 lumen per square meter = 1 meter-candela	
	Footcandles	Lux	
Footcandles	1	0.0929	
Lux	10.76	1	
B. Luminance			
1 footlambert = 1 lumen per square foot		1 nit = 1 candela per square meter	
	Foot-lamberts	Candelas per square meter	Candelas per square foot
Footlamberts	1	0.2919	3,142
Candelas per sq m	3,426	1	10.76
Candelas per sq ft	0.3183	0.0929	1

product of the solid angle of the cone, and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. More simply, it is the luminous intensity of any surface in a given direction per unit of projected area of the surface viewed from that direction (see Table 26-1).

Candela per square meter is the SI unit of luminance when the meter is taken as the unit of length. Another term for this unit is the nit, which is not commonly used in North America. The candela per square foot is the inch-pound unit of luminance when the foot is the unit of length.

Footlambert is a former unit of luminance, and is equal to $1/\pi \text{ cd/ft}^2$, or to the uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of 1 lm/ft^2 , or to the average luminance of any surface emitting or reflecting light at that rate. The term footlambert is now obsolete, and its use is deprecated.

Luminous Efficacy. This is a quantity denoting the energy effectiveness of light sources. It is the ratio of the total luminous flux (lumens) to the total power input (watts). The maximum luminous efficacy of an *ideal* white source, defined as a radiator with constant output over the visible spectrum, is approximately 200 lm/W .

Reflectance. Reflectance ρ is the ratio of reflected flux to incident flux. Measured values of reflectance depend upon the angles of incidence and view, and on the spectral character of the incident flux. Because of the dependence, the angles of incidence and view and this spectral characteristics of the source should be specified.

Transmittance. Transmittance τ is the ratio of the transmitted flux to the incident flux. Measured values of transmittance depend upon the angle of incidence, the method of measurement of the transmitted flux, and the spectral character of the incident flux. Because of this dependence, complete information of the technique and conditions of measurement should be specified.

Absorptance. Absorptance α is the ratio of the flux absorbed by a medium to the incident flux. The sum of reflectance, transmittance, and absorptance is one.

Brightness. This term refers to the intensity of sensation resulting from viewing light source and surfaces. This sensation is determined in part by the measurable luminance defined above and in part by conditions of observation such as the state of adaptation of the eye.

Color. Within the visible spectrum, wavelengths are distinguished one from another by their ability to excite in the human eye various color sensations. Thus the shorter wavelengths excite the color known as violet, and as the wavelengths increase, the color sensation gradually changes through blue, green, yellow, and orange, and finally to red at the longer wavelengths of the visible spectrum. The color of the sensation produced by light of a composite character is determined by its spectral power distribution. Color is defined as that quality of visual sensation which is associated with the spectral distribution of light. Color matching is the process of adjusting the color of one area so that it is the same color as another.

Correlated color temperature (CCT) of a light source is the absolute temperature (in Kelvin) of a blackbody radiator whose chromaticity most nearly resembles that of the light source. CCT refers to the whiteness of the light that a source emits. Low CCT light appears more yellow or red, and is generally considered to be warm in appearance, while high CCT light appears more bluish white. A neutral CCT is generally considered to be around 3500 K .

Color rendering is a general expression for the effect of a light source on the color appearance of objects in conscious or subconscious comparison with their color appearance under a reference light source.

The Color rendering index (CRI) of a light source is the measure of the degree of color shift which objects undergo when illuminated by the light source, as compared with the color of those same objects when illuminated by a reference source of comparable color temperature. Values for common light source vary from about 20 to 99. The higher the number, the better the color rendering

TABLE 26-3 Color Temperature and Color Rendition Index of Some Common Light Sources*

Light source	Correlated color temperature, K	Color rendering index
“Cool” fluorescent		
Standard cool white ES [†]	4150	62
Cool white, ES, RE741, phosphor	4100	72
Lite white, ES	4200	49
RE841 phosphor	4100	80
“Warm” fluorescent		
Standard warm white, ES	3000	52
Warm white, ES, RE730 phosphor	3000	70
RE830 phosphor	3000	82
RE827	2700	82
Deluxe daylight fluorescent, ES	6500	84
RE950	5000	90
Incandescent		
General service	2600–3100	89–92
Tungsten-halogen	2900–3100	90
High-intensity discharge		
Mercury	5710	15
Mercury improved color	4430	32
Metal halide, clear	4000	65
Metal halide, ceramic	3000	80–88
Metal halide, ceramic	4200	90
High-pressure sodium	2100	21
Daylight		
Overcast sky	6000–7000	
Blue sky	11,000–25,000	
Sun, outside of earth’s atmosphere	6500	

*Check manufacturer’s technical literature for current data.

[†]Energy-saving models.

(see Table 26-3). CRI should only be used to compare sources of the same color temperature since different reference sources are used at different color temperature. A black body radiator is used at low CCT’s and daylight spectra are used at high CCT’s.

REFERENCE ON QUANTITIES, UNITS, AND CONVERSION FACTORS

1. *American National Standard Nomenclature and Definitions for Illuminating Engineering, RP-16-05, Illuminating Engineering Society of North America.*

26.3 INCANDESCENT LAMPS

Incandescent Filament Lamps. These are light sources in which light is produced by a filament heated to incandescence by an electric current. Of all commonly used light sources, incandescent lamps have the lowest initial cost, lowest luminous efficacy, and shortest life. As shown in Fig. 26-3, the major parts on an incandescent filament lamp are the filament, bulb, base and fill gas.

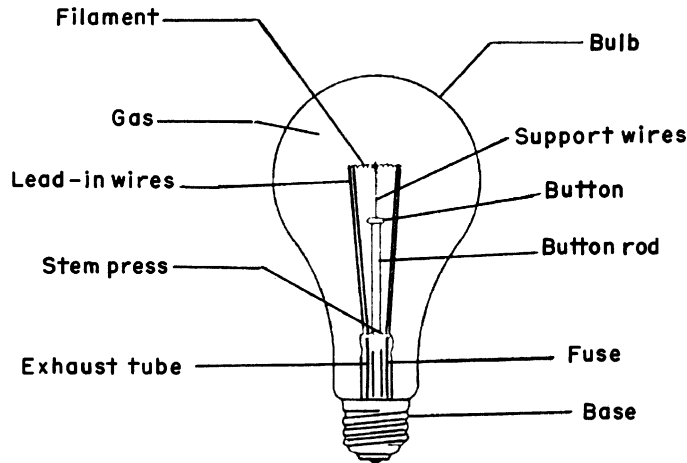


FIGURE 26-3 Incandescent filament lamp construction.

Filament. The efficacy of light production by incandescent lamps depends on the temperature of the filament. Tungsten, because of its high melting point (3655 K), higher than that of all other elements except carbon, is the most common filament material used today. Filament forms, sizes, and support constructions vary with different types of lamps. Most filaments are coiled one or more times to increase the filament temperature, light output, and the lamp's luminous efficacy.

Mechanical problems associated with tungsten filaments make the incandescent lamp an inherently compact, somewhat spherical structure. The filament's length and diameter limit its range of operation between 1.5 and 300 V. At 1.5 V, the filament is very short and thick, and it becomes difficult to heat it without excessively heating its support wires. The lamps in the low-voltage (6-to 12-V) class, however, are relatively rugged and will withstand the shocks of motor-vehicle and similar applications. At voltages near 30 V, the filament is very long and slender; it is fragile and difficult to support.

Bulbs. Bulb shape, size, material, and finish vary according to application needs. Shapes range from tubular to spherical and from parabolic to flame form. Bulbs are designated by a letter referring to the shape (see Fig. 26-4) and by a number which is the maximum diameter in eighths of an inch; for example, A-19 designates an A-shaped bulb with a diameter of 19/8 or 2-3/8 in.

Most bulbs are made of lead or lime soft glass, although heat-resisting hard glass is used for high-temperature application, and are frosted on the inside for moderate diffusion of the light without appreciably reducing light output. Clear, unfrosted lamps are used where accurate control of light is needed from a point or line source. Fused quartz and high-silica glass are used for other lamps.

Base Types. These also vary according to application needs. They range from screw types for most general-service lamps to bipost and prefocus types where a high degree of accuracy in lamp positioning is important, such as in projection systems. Figure 26-5 shows some typical base shapes. Base size varies with lamp wattage, for heat dissipation, and voltage. For outdoor lighting, use brass-base lamps.

Fill Gas. This is used in incandescent-filament lamps to reduce the rate of evaporation of the heated filament. Inert gases such as nitrogen, argon, and krypton are in common use today, with krypton used where its increased cost is justified by increased efficacy or increased lamp life. For example, the 90-W krypton "energy-saving" lamp produces 4% less light, but one-third longer rated life compared with the standard 100-W lamp.

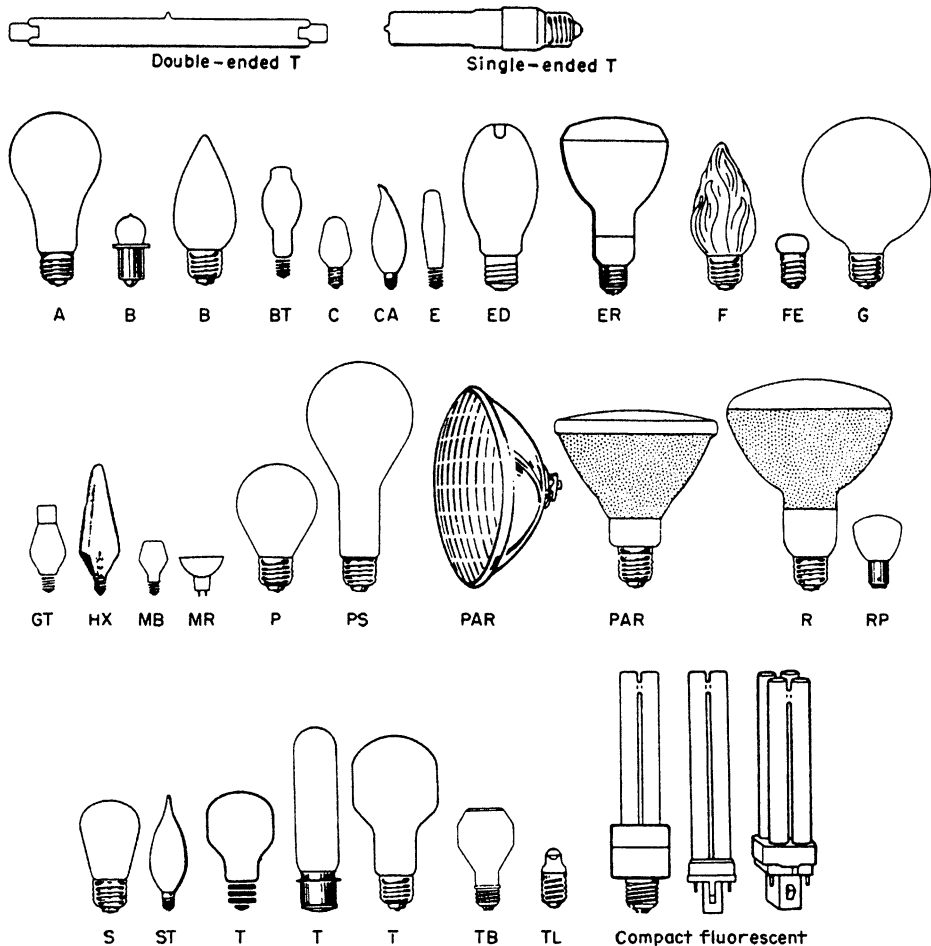


FIGURE 26-4 Typical bulb shapes and designations (not to scale). Most high intensity discharge (HID) lamps use BT-, E-, ED-, PAR-, and R-shape bulbs.

Many regular, tubular, and PAR shaped lamps are available with a halogen fill gas, for better lumen maintenance, improved light output, and/or longer life. Called “tungsten halogen,” their filaments operate at temperatures higher than regular incandescent lamps, producing light of greater color temperature, plus longer life for a given light output. For applications justifying the increased lamp cost, a 90-W, 2000-h tungsten halogen lamp, for example, has only 8% less light output rating than the standard 100-W, 750-h lamp, with improved lumen maintenance through its longer life.

Energy Characteristics. Only a small percentage of the total radiation from incandescent lamps is in the visible spectrum, with the majority in the infrared spectrum. As the filament temperature is increased, the luminous efficacy increases with a maximum of 53 lm/W for an uncoiled tungsten wire at its melting point. To obtain life, practical lamps operate at a temperature well below the melting point.

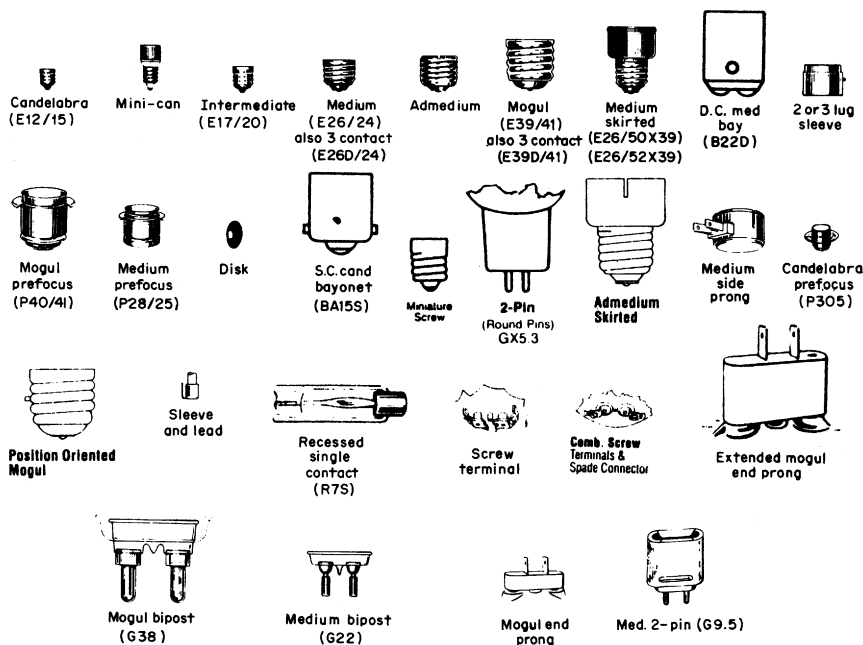


FIGURE 26-5 Common incandescent and HID lamp bases (not to scale). IEC designations are shown where available.

Performance Characteristics. The performance of tungsten-filament lamps is affected by voltage, position of the bulb (if incorrect), size, construction, ambient temperature (if excessive), and quality of manufacture. The voltage characteristics through a range of a few volts above and below design volts may be expressed as simple exponential equations in the following relationships, where capitalized terms represent normal rated values:

$$\frac{\text{Life}}{\text{LIFE}} = \left(\frac{\text{LUMENS}}{\text{lumens}} \right)^a = \left(\frac{\text{LUMENS / WATT}}{\text{lumens / watt}} \right)^b = \left(\frac{\text{VOLTS}}{\text{volts}} \right)^d = \left(\frac{\text{AMPS}}{\text{amps}} \right)^u$$

$$\frac{\text{Lumens}}{\text{LUMENS}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^k = \left(\frac{\text{lumens / watt}}{\text{LUMENS / WATT}} \right)^h = \left(\frac{\text{watts}}{\text{WATTS}} \right)^s = \left(\frac{\text{amps}}{\text{AMPS}} \right)^y = \left(\frac{\text{ohms}}{\text{OHMS}} \right)^z$$

$$\frac{\text{LUMENS / WATT}}{\text{lumens / watt}} = \left(\frac{\text{LUMENS}}{\text{lumens}} \right)^f = \left(\frac{\text{VOLTS}}{\text{volts}} \right)^g = \left(\frac{\text{AMPS}}{\text{amps}} \right)^j$$

$$\frac{\text{amps}}{\text{AMPS}} = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^t \quad \text{and} \quad \left(\frac{\text{watts}}{\text{WATTS}} \right) = \left(\frac{\text{volts}}{\text{VOLTS}} \right)^n$$

Exponents d , k , and t are taken as fundamentals, and other exponents are derived from them. A list of exponents is given in the following table. Values given apply to lamps operated at 90% to 110% rated voltage. Outside that range, use the values from Fig. 26-6.

The theoretical life of lamps calculated by the exponential relationship of life and voltage is seldom realized in practical installations in the case of excessive “undervoltage” burning, since handling, cleaning, vibration, etc., introduce breakage factors which tend to reduce lamp life.

	Exponents	
	Gas-filled	Vacuum
<i>a</i>	3.86	3.85
<i>b</i>	7.1	7.0
<i>d</i>	13.1	13.5
<i>u</i>	24.1	23.3
<i>k</i>	3.38	3.51
<i>h</i>	1.84	1.82
<i>s</i>	2.19	2.22
<i>y</i>	6.25	6.05
<i>z</i>	7.36	8.36
<i>f</i>	0.544	0.550
<i>g</i>	1.84	1.93
<i>j</i>	3.40	3.33
<i>t</i>	0.541	0.580
<i>n</i>	1.54	1.58

Lamp Lumen Depreciation. Because of filament evaporation throughout life, the filament of a lamp becomes thinner and thus consumes less power. The light output decreases as the lamp progresses through life because of lower filament temperature and bulb blackening. Figure 27-7a shows the change in watts, amperes, lumens per watt, and lumens for a 200-W general-service lamp on constant-voltage service. The minor quantity of bromine or iodine in tungsten-halogen lamps vaporizes during operation, and acts to return particles of tungsten back to the filament. This results in superior lumen maintenance.

Lamp Mortality and Renewal Rate. Lamp life is based on data obtained from lifetesting a large number of lamps. A perfect mortality record would be one in which all lamps reached their rated life and then burned out. However, many factors inherent in lamp manufacture and lamp materials make it impossible for each individual lamp to operate for exactly the life for which it was designed. A typical mortality curve of a large group of lamps is illustrated in Fig. 26-7b, where it is superimposed on a lumen depreciation curve from Fig. 26-7a.

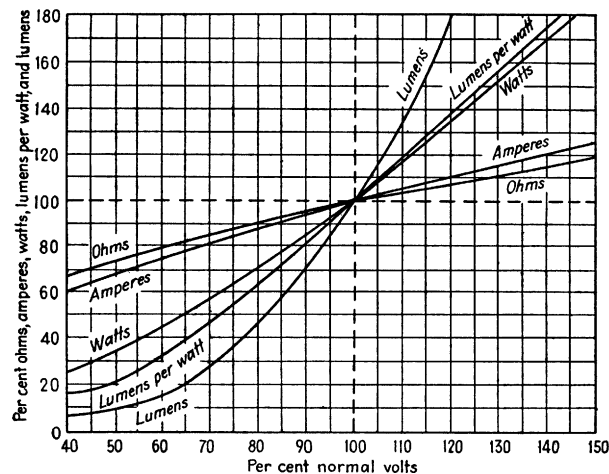


FIGURE 26-6 Characteristic curves for large gas-filled lamps showing the effect of operating a lamp at other than its rated voltage. These characteristic curves are averages of many lamps.

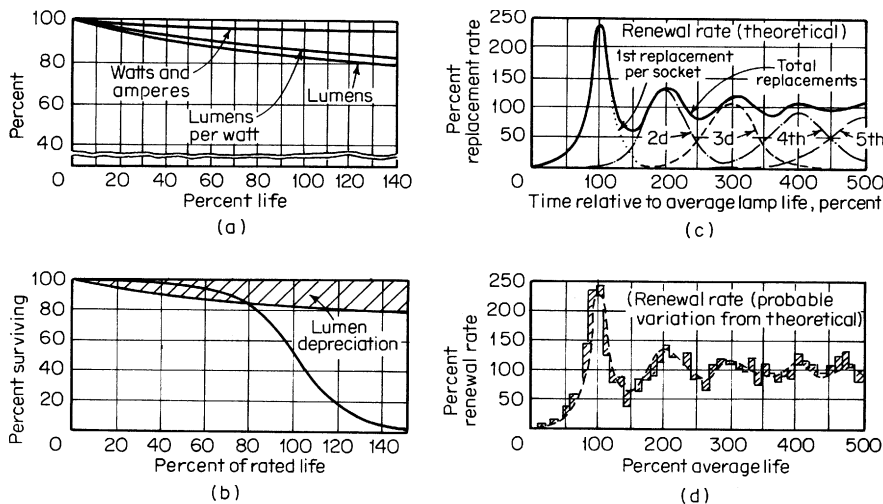


FIGURE 26-7 Life characteristics and renewal rate.

The mortality curve influences the rate of lamp replacements for installations involving a large number of lamps. If individual lamps are replaced as they burn out, the replacement rate is as shown in Fig. 26-7c. In a new installation relatively few burnouts would be expected during the first several hundred hours of operation, but as the design life is approached, the rate of burnout increases rapidly. After a burning period of 4 to 5 times the average lamp life, the renewal rate fluctuation finally reaches a steady or normal rate.

The dotted curve in Fig. 26-7c showing the theoretical rate of renewals holds only for an infinitely large installation. Departures from this curve in practical installations will, by the law of probability, more likely be represented by the solid block-shaped pattern. The larger the installation, the more closely the two curves tend to coincide. Complaints on life are occasionally encountered during those periods when chance dictates that renewals run higher than average, even though a record of the actual number of renewals over an extended period of time would show average rated life had been obtained.

Rated Lamp Life. The rated life of a lamp is generally defined as the operating hours at which 50% of a representative group of lamp burned under correct operating conditions on a 60-Hz circuit are still burning, and ranges from 750 to 1500 h for the general-service incandescent types. As compared with life in the laboratory under controlled operating conditions, performance in service may differ widely. Lamp breakage and fluctuating line voltage tend to shorten life. Line-potential drop with resultant low-voltage operation often tends to lengthen life. Extended-service lamps with a rated of 2500 h and longer are available in a range of sizes from 15 to 1000 W. They give less light than standard lamps under normal conditions but may be economically justified when labor costs to replace lamps are very high.

Influence of operating Conditions on Lamp Performance. Tests show that ambient temperatures have little effect on performance characteristics. Very high temperatures, however, may cause mechanical difficulties. On direct current, although the mortality rate is lower, the maintenance of light output is poorer than on alternating current. Intermittent operation in general (not sign-flashing service) does not materially affect lamp performance. There is a reason to believe that lamp life is shortened by voltage fluctuations, even though the voltage excess averaged over the life of the lamp is offset by an equal average voltage deficiency.

Except in the case of lamps designed for a particular position of operation, operating position has little effect on lamp performance. Shock and vibration are likely to impair the performance of lamps

with filaments of small diameter to a greater extent than in the case of lamps with filaments of large diameter. Special types of lamps are available for use in installations where vibration is likely to be encountered and others, known as “rough-service” lamps, for use where they are likely to be subjected to shock. Neither of these two lamps will function properly in place of the other.

Classes of Incandescent Lamps. Incandescent lamps are divided and cataloged by manufactures into three major groups: large lamps, miniature lamps, and photographic lamps. Large lamps are those normally used for interior and exterior general and task lighting. Miniature lamps are generally used in automotive, aircraft, and appliance applications. Photographic lamps, as the name implies, are used in photography and projection service. Some of the main classes of large lamps are as follows:

General Service. These are for general lighting on 120-V circuits (see Table 26-4). Sizes range from 15 to 1500 W with efficacies of 8 to nearly 23 lm/W. Lamps rated at 130 V and other voltages are also available—consult catalogs or sales representatives of lamp manufactures for specific listings.

High Voltage. High-voltage incandescent lamps are designed for operation directly on circuits of 220 to 300 V. They are less rugged and have a lower efficacy than general-service lamps. There are also general-service incandescent lamps of 277-V circuits. One manufacturer cautions that such lamps be enclosed if used on high-capacity, low impedance electrical distribution systems.

Extended Service. These have a life of 2500 h or more and are intended for use in applications where a lamp failure causes an inconvenience, a nuisance, or a hazard to replace the lamp, or where replacement labor is expensive (see Table 26-5). They are less efficient than general-service lamps.

TABLE 26-4 General-Service Lamps for 120-V Circuits*

(Will operate in any position, but lumen maintenance is best for 40 to 1500 W when burned vertically base up)

Watts	Bulb and other description	Base	Rated average life, h	Maximum overall length, in	Approximate initial lumens	Rated initial lumens per watt	Depreciation factor, % output at 70% rated life
15	A-15 inside frosted	Med.	2500	3 1/2	125	8.3	83
25	A-19 soft white	Med.	2500	4 1/2	210	8.4	
34 [†]	A-19 diffuse coating	Med.	2000	4 7/16	380	11.1	
40	A-19 inside frosted	Med.	1000	4 7/16	505	12.6	
52 [†]	A-19 diffuse coating or clear	Med.	1330	4 7/16	730	14.0	
60	A-19 inside frosted	Med.	1000	4 7/16	865	14.4	93
67 [†]	A-19 diffuse coating	Med.	1000	4 7/16	1,030	16.9	
75	A-19 inside frosted	Med.	750	4 7/16	1,190	15.9	92
90 [†]	A-19 diffuse coating	Med.	1000	4 7/16	1,465	16.3	
100	A-19 inside frosted	Med.	750	4 7/16	1,710	17.1	90.5
135 [†]	A-21 diffuse coating	Med.	1000	5 3/8	2,380	17.6	
150	A-21 inside frosted or clear	Med.	750	5 3/8	2,850	19.0	89
200	A-23 inside frosted or clear	Med.	750	6 5/16	3,920	19.6	89.5
300	PS-25 clear or inside frosted	Med.	750	6 15/16	6,200	20.7	87.5
300	PS-35 clear or inside frosted	Mog.	1000	9 3/8	5,820	19.4	86
500	PS-35 clear	Mog.	1000	9 3/8	10,850	21.7	89
750	PS-52 clear	Mog.	1000	13	17,040	22.7	89
1000	PS-52 clear or inside frosted	Mog.	1000	13	23,740	23.7	89
1500	PS-52 clear or inside frosted	Mog.	1000	13	34,400	22.9	78

*Consult manufacturers' technical literature for current data, as values change frequently.

[†]Reduced wattage, krypton-fill type.

Note: 1 in = 25.4 mm.

TABLE 26-5 Extended Service (2500-h Rated Life) Incandescent Filament Lamps*
(For 120 V)

Watts	Bulb and Finish	Base	Maximum overall length, in	Approximate initial lumens	Rated initial lumens per watt	Depreciation factor, % output at 70% rated life
19 [†]	Soft-white	Med.	3 ¹ / ₂	110	7.3	
25	A-19 soft white	Med.	4 ¹ / ₄	210	8.4	79
34 [†]	A-19 diffuse coating	Med.	4 ⁷ / ₁₆	375	11.0	
67 [†]	A-19 diffuse coating	Med.	4 ⁷ / ₁₆	940	14.0	
90 [†]	A-19 diffuse coating	Med.	4 ⁷ / ₁₆	1285	14.3	
100	A-19 diffuse coating	Med.	4 ⁷ / ₁₆	1440	14.4	92.5
135 [†]	A-19 diffuse coating	Med.	5 ³ / ₈	2100	15.6	
150	A-23 inside frosted	Med.	6 ⁵ / ₁₆	2350	15.7	89
150	PS-25 inside frosted	Med.	6 ¹⁵ / ₁₆	2250	15.0	85.5
200	A-23 inside frosted and clear	Med.	6 ³ / ₁₆	3320	16.6	87.5
300	PS-30 inside frosted and clear	Med.	8 ¹ / ₁₆	5190	17.3	79
300	PS-35 inside frosted and clear	Mog.	9 ³ / ₈	5190	17.3	84
500	PS-40 inside frosted and clear	Mog.	9 ³ / ₄	9070	18.1	80

*Consult manufacturers' technical literature for current data, as values change frequently.

[†]Reduced wattage, krypton-fill type. Electrical, light output, and life ratings are different for various manufacturers.**Note:** 1 in = 25.4 mm.

General Lighting Tungsten-Halogen. These are compact, have better lumen maintenance, and provide a whiter light and a longer life. Some typical lamps for general lighting are listed in Table 26-6.

Reflectorized. These are a group of lamps embodying integral reflecting surfaces. Bowl-silvered lamps are employed in direct-lighting equipment in which it is desired to shield the filament from view in direct or indirect equipment. Initial loss of light output due to the silvering is 6% to 10%; the rate of decline of light output is considerably greater than in clear-bulb lamps of corresponding sizes—60% to 80% greater in the case of 100- and 200-W lamps. However, a luminaire (of similar distribution) with an unprocessed lamp may produce less light because of poorer maintenance.

In projector flood- and spotlight-lamps, the bulb is constructed of a molded bowl-shaped section of parabolic or other suitable profile, on the inner surface of which is a metal-reflecting surface (see Table 26-6). This bowl is fused to a molded-glass cover plate, which may be clear or may consist of a pattern of lenses and prisms, depending on the desired beam characteristics. Reflector-type lamps are constructed with blown bulbs of suitable profiles (usually cylindrical for showcase lighting or parabolic for spotlighting) having parts of the inner surfaces covered with a reflecting metallic film. Their nominal life is usually 2000 h.

The National Energy Policy Act (EPACT) of 1992 prohibited the manufacture after October 31, 1995 of certain standard, general-service 115- to 130-V reflector and projector lamps. Among those obsoleted were 50-, 75-, and 100-W R-40 lamps and 75-, 100-, and 150-W R-40 and PAR-38 lamps. They are replaced by higher-efficiency halogen-capsule lamps.

A number of projector lamps are available with dichroic filters (interference films) to control the spectral quality of the radiation in such a manner as to separate the heat from the light in the beam or to produce colored light without the usual losses due to absorption by filters. From 75% to 80% of the heat can be removed from the beam at a sacrifice of only 15% to 20% of the light. These "cool beam" lamps must be used in luminaires that are capable of dissipating the additional heat that remains within the luminaire. Colored dichroic lamps produce more deeply saturated colors with higher efficacy than is obtainable with color filters.

In certain PAR-bulb lamps, the tungsten-halogen capsule has an infrared coating, enabling a lower power rating by redirecting energy back to the filament (Table 26-7). All applications of reflectorized lamps should follow the recommendations of the manufacturer concerning luminaire

TABLE 26-6 Tungsten-Halogen Lamps for General Lighting*

Watts	Volts	Bulb and Finish	Base†	Maximum overall length, in	Rated life, h	Approximate initial lumens	Approximate initial lumens per watt	Depreciation factor, % output at 70% rated life
Double-ended types								
200	120	T-3 clear	RSC	3 ¹ / ₈	1500	3,460	17.3	96
300	120	T-3 clear	RSC	4 ¹¹ / ₁₆	2000	5,950	19.9	
300	120	T-4 clear	RSC	3 ¹ / ₈	2000	5,650	18.5	
400	120	T-4 clear	RSC	3 ¹ / ₈	2000	7,750	19.4	96
500	120	T-3 clear	RSC	4 ¹¹ / ₁₆	2000	11,100	22.2	96
1000	120	T-6 clear	RSC	5 ³ / ₈	2000	23,400	23.4	96
1000	220	T-3 clear	RSC	10 ³ / ₁₆	2000	21,500	21.5	96
1500	220	T-3 clear	RSC	10 ³ / ₁₆	2000	35,800	23.9	96
Single-ended types								
50	120	TB-19 I. F.	Med. screw	4 ⁷ / ₁₆	2000	710	14.2	96
90	120	TB-19 I. F.	Med. screw	4 ⁷ / ₁₆	2000	1,580	17.6	
100	120	T-4 clear	Minican	2 ¹³ / ₁₆	2000	1,600	16.0	
150	120	T-4 clear	Minican	3	2000	2,800	18.7	96
250	120	T-4 clear	Minican	3 ³ / ₃₂	2000	4,850	19.4	
250	120	T-4 clear	D. C. Bay.	3	2000	4,850	20.0	
500	120	T-4 frosted	D. C. Bay.	3 ⁷ / ₁₆	2000	10,100	20.2	

*Consult manufacturer's technical literature for current data, as values change frequently.

†RSC = recessed single contact.

Note: 1 in = 25.4 mm.**TABLE 26-7** Basic Data on 120 V PAR Lamps

Lamp shape	Wattage	Distributions available*	Center beam candlepower	Lumens	MOL
Standard halogen					
PAR 16	50	FL	640	400	2.88
	60	NSP, NFL	5000, 3100	650	2.88
	75	NSP, NFL	7500, 1900	900	2.88
PAR 20	35	NSP, NFL, WFL	3000, 800, 500	360	3.13
	50	NSP, NFL, WFL	4600, 1200, 900	550	3.13
PAR 30	50	NSP, NFL, FL	8800, 2300, 1300	900	3.62
	60	NSP, NFL, FL	12000, 2775, 1550	860	3.62
	75	NSP, NFL, FL	15400, 4000, 2100	1130	3.62
PAR38	45	SP, WSP, FL, WFL	1500, 700	560	5.31
	50	SP, FL	10500, 1850	650	5.31
	60	SP, WSP, NFL, FL	16000, 10500, 3700, 2500	850	5.31
	75	SP, WSP, FL, WFL	19200, 12300, 3150, 1300	1060	5.31
	90	SP, WSP, NFL, FL, WFL	19000, 14300, 4700, 3500, 1600	3110	5.31
	100	SP, FL	22000, 4000	1500	5.31
	120	SP, NFL, FL, WFL	22500, 7700, 4600, 2000	1800	5.31
	250	SP, FL	46500, 9000	3600	5.31
PAR 56	500	NSP, MFL, WFL‡	78500, 40000, 19500	8800	5
PAR 64	1000	NSP, MFL, WFL‡	135000, 82000, 23000	19400	6
Halogen IR lamps					
PAR 30 IR	40	NSP, NFL, FL	8800, 2300	680	3.62
	50	NSP, NFL, FL	13000, 2900, 1400	900	3.62
PAR 38 IR	50	SP, NFL	4000, 3000	850	5.31
	55	SP, FL	14000, 2500	800	5.31
	60	SP, WSP, NFL, FL	20000, 12000, 5000, 3600	1110	5.31
	80	SP, FL	25000, 5500	1500	5.31
	100	FL, NFL, FL	29000, 6300, 3400	2070	5.31

*Beam spread for distributions are: VNSP 5°, NSP 9°, SP 9°, WSP 12°, NFL 25°, FL 30°, WFL 40 or 50°.

‡8 × 15, 11 × 30, 20 × 45 degree beam spreads.

‡8 × 20, 10 × 30, 20 × 60 degree beam spreads.

design, lamp burning position, maximum wattage, limits on bulb and base temperatures, screens to protect people and surroundings, etc.

Small Tungsten-Halogen Lamps. Families of 13/8- and 2- in-diameter, 12-V models having internal multifaceted reflectors, providing a range of beam spreads for accent and display lighting, are available. Dichroic reflector coatings reduce approximately two-thirds of the heat in the beam by emitting infrared energy to the rear, thus decreasing fading of color-perishable items that the illuminated. Small changes in applied voltage have large effects on lamp life, and rapid on-off operation will shorten life. Dimmers recommended for the inductive loads of the step-down transformers should be used instead of incandescent-type dimmers. Blackening of the tungsten-halogen capsule which may result from dimming can be cleared up by full 12-V operation.

Rough and Vibration Service. These lamps are for use where lamps are subjected to shock and vibration while in use. filament construction differs. Rough-service lamps are available from 25 to 200 W, while those for vibration service range from 40 to 150 W.

Decorative Lamps. Incandescent lamps in many bulb shapes, bases, and wattages are available for a variety of decorative and architectural lighting applications. Some have specific requirements regarding burning position, shielding from moisture, etc., as covered in technical literature of the manufacturer.

26.4 FLUORESCENT LAMPS

Fluorescent lamps are low-pressure mercury electric-discharge lamps in which a phosphor coating transforms of the ultraviolet energy generated by the discharge arc into light. The major parts of a fluorescent lamp (hot-cathode type) are the bulb (tube), electrodes, fill gas, phosphor coating, and bases, as shown in Fig. 26-8. When the proper voltage is applied across the ends of the lamp, an arc is produced by current flowing between the electrodes through the fill gas (mercury vapor). This discharge generates some visible radiation, but mostly ultraviolet at 253.7 nm, which in turn excites the phosphor coating to emit light.

Fluorescent lamps are available commercially principally in four distinct types, depending upon their operating circuits: (1) hot-cathode, preheat-starting; (2) hot-cathode, instant-starting; (3) hot-cathode rapid-start; and (4) cold-cathode.

Bulb. Fluorescent lamp bulbs are basically tubular of small cross-sectional diameter. The bulb is available in straight, U-shaped, and circular configurations in bulb diameters from 1/4 to 21/8 in. In straight lengths, they range from 6 to 96 in (nominal). Shorter lamps, such as the 22-, 34-, and 46-in T-5 lamps, can simplify the design of luminaires for 600- and 1200-mm module ceiling systems. Circular (circuline) lamps have nominal overall diameters from 6 1/2 to 16 in. U-shaped lamps are 24 in (hot-cathode) and 45 in (cold-cathode) in nominal overall length. Fluorescent lamps are designated by a letter indicating the tube cross section shape and a number indicating the diameter in eighths of an inch. A T-8 lamp has a tubular bulb of 1 in diameter. Smaller diameter lamps and lower height ballasts can result in "thinner" luminaires. See Table 26-8 for a collection of typical fluorescent lamp size and wattages.

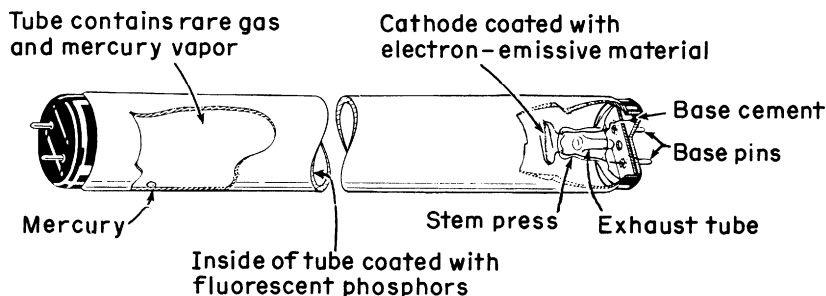


FIGURE 26-8 Cutaway view of fluorescent hot-cathode preheat-starting lamp.

TABLE 26-8 Typical Fluorescent Lamps^a

Lamp Wattage, W	Nominal length, in ^b	Bulb	Base	Rated life, h ^c	CRI ^d	Initial lumens ^e
Preheat start—requires separate starter or starting switch						
4	6	T-5	Miniature bipin	6,000	62	135
6	8.6	T-2	Axial	10,000	82	310
6	9	T-5	Miniature bipin	7,500	62	295
8	12.6	T-2	Axial	10,000	82	500
8	12	T-5	Miniature bipin	7,500	62	400
11	16.6	T-2	Axial	10,000	82	680
13	20.6	T-2	Axial	10,000	82	860
13	21	T-5	Miniature bipin	7,500	62	850
13	12	T-8	Medium bipin	7,500	62	565
14	15	T-8	Medium bipin	7,500	62	685
14	15	T-12	Medium bipin	9,000	62	650
15	18	T-8	Medium bipin	9,000	62	825
15	18	T-12	Medium bipin	9,000	62	760
20	24	T-12	Medium bipin	9,000	62	1,200
30	36	T-8	Medium bipin	7,500	62	2,175
82 ^f	60	T-17	Mogul bipin	9,000	62	5,750
90	60	T-17	Mogul bipin	9,000	62	6,000
Rapid start—straight lamps						
14	22	T-5	Miniature bipin	20,000	85	1,350
17	24	T-8	Medium bipin	20,000	75	1,325
21	34	T-5	Miniature bipin	20,000	85	2,100
25	36	T-8	Medium bipin	20,000	75	2,080
25 ^f	36	T-12	Medium bipin	18,000	62	1,925
28	46	T-5	Miniature bipin	20,000	85	2,900
25 ^k	48	T-12	Medium bipin	12,000	62	1,860
28 ^{f,g}	48	T-12	Medium bipin	18,000	49	2,475
30	36	T-12	Medium bipin	18,000	62	2,275
32	48	T-8	Medium bipin	20,000	75	2,850
32	48	T-8	Medium bipin	20,000	80	2,950
32 ^f	48	T-12	Medium bipin	15,000	62	2,525
32 ^f	48	T-12	Medium bipin	15,000	49	2,700
34 ^f	48	T-12	Medium bipin	20,000	62	2,650
34 ^f	48	T-12	Medium bipin	20,000	72	2,750
34 ^f	48	T-12	Medium bipin	20,000	49	2,825
35	58	T-5	Miniature bipin	20,000	85	3,650
35HO	24	T-12	Recessed DC	9,000	62	1,620
40	48	T-12	Medium bipin	24,000	73	3,300
40	48	T-12	Medium bipin	24,000	80	3,400
40	60	T-8	Medium bipin	20,000	75	3,600
45HO	36	T-12	Recessed DC	9,000	62	2,800
60HO	48	T-12	Recessed DC	12,000	62	4,050
85HO	72	T-12	Recessed DC	12,000	62	6,350
95HO	96	T-12	Recessed DC	12,000	62	8,000
110HO	48	T-12	Recessed DC	10,000	62	6,200
110HO	96	T-12	Recessed DC	12,000 ^j	72	9,200
185HO	96	T-12	Recessed DC	9,000 ^j	62	12,500
215HO	96	T-12	Recessed DC	10,000 ^j	62	13,500
215PG	96	PG-17	Recessed DC	12,000 ^j	62	15,000

TABLE 26-8 Typical Fluorescent Lamps^a (Continued)

Lamp Wattage, W	Nominal length, in ^b	Bulb	Base	Rated life, h ^c	CRI ^d	Initial lumens ^e
Rapid start—U-shaped lamps						
31U/1 ³ / ₈	22 ¹ / ₂	T-8	Medium bipin	20,000	82	2,725
32U/6	22 ¹ / ₂	T-8	Medium bipin	20,000	75	2,700
35U/3 ^f	22 ¹ / ₂	T-12	Medium bipin	18,000	62	2,350
34U/6 ^f	22 ¹ / ₂	T-12	Medium bipin	18,000	70	2730
40U/3	22 ¹ / ₂	T-12	Medium bipin	18,000	70	2925
40U/6	22 ¹ / ₂	T-12	Medium bipin	18,000	70	3050

^aCheck manufacturers' technical literature for current data, as values change frequently.

^bIncludes lamp and two standard lampholders, except RS T-5 lamps.

^cLamp burning hours to median life expectancy, when operated 3 h per start. More frequent starting reduces life and less frequent starting increases life. Some energy-saving lamps on single-lamp ballasts may have shorter life. Ballast strongly affects lamp life.

^dColor rendering index (CRI); rates ability to render color of objects on a scale of 0 to 100. Numerical values should be compared only for lamps of the same color temperature.

^eAfter 100 burning hours. Consult ballast or luminaire manufacturer for appropriate multiplier (*ballast factor*). Some lamp catalogs also give mean or design lumens.

^fUse in 60°F or higher ambients, protect lamp surfaces from strong air drafts, and check manufacturer about operation on dimming, reduced current, or cathode cutout systems.

^gBased on 12 h per start.

U-shaped models employing $\frac{1}{2}$ - or $\frac{5}{8}$ -in-diameter bulbs with little separation between the legs are called "compact fluorescent." in lengths below 9 in, they can have one or more twin tubes. Family designations vary. Subminiature hot- and cold- cathode tubular types are 0.25 and 0.266 in in diameter, respectively, and with lengths from 4 to 20 in.

Electrodes. There are two electrodes in each fluorescent lamp, one at each end, designed to operate as either "hot" or "cold" electrodes (or cathodes).

Hot-cathode lamps contain electrodes which are usually coiled-coil (or triple-coiled) tungsten filaments coated with one or more of the alkaline-earth oxides. By suitable circuit arrangements these cathodes can be heated to an electron-emitting temperature before the arc strikes, or they may be required to act momentarily as cold cathodes until they are heated by bombardment after the lamps have started. Lamps using these cathodes may be designed to carry currents of 1 to 2 A with low-voltage drop (10 to 12 V) at the electrodes. Some energy-saving types of rapid-start ballasts have disconnect elements to discontinue cathode heating after the lamp starts. The power saved is approximately 3 W per lamp. Metal shields can be used to minimize end darkening, improving lamp lumen maintenance.

Cold-cathode lamps are those that use electrodes of tubular form of iron or nickel which may be coated on their inside surfaces with electron-emitting materials. These cathodes operate at temperatures which limit the lamps to low-current densities. The electrode drop in these lamps is relatively high (over 50 V), but they are not subject to short life as a result of frequent instant starting.

Fill Gas. Droplets of liquid mercury are present in the fluorescent lamp and vaporize to a very low pressure during lamp operation. Argon is added to assist ignition of the discharge in standard lamps, while energy-saving types have an argon-krypton mixture. Certain other types use a combination of argon and neon or argon, neon, and xenon.

Phosphors. The chemical composition of the phosphor coating on the bulb interior surface determines the color of the light produced and, in part, lamp efficacy. Those lamps with phosphors producing good overall color rendering are generally of higher efficacy. Figure 26-9 shows typical spectral power distributions for a variety of different phosphor compositions.

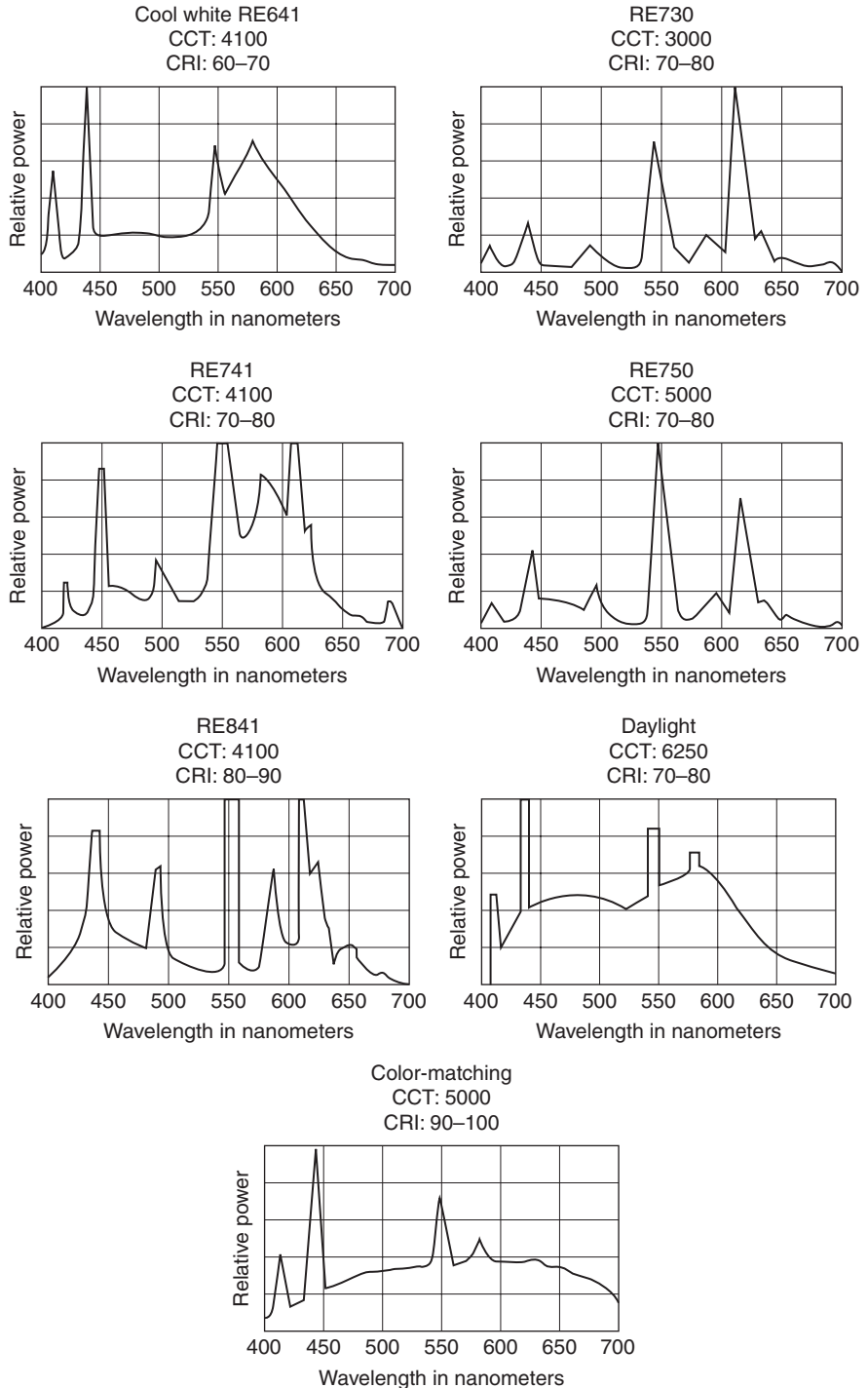


FIGURE 26-9 Spectral distribution curves for typical fluorescent lamps. (Reprinted from the IESNA Lighting Handbook 9th ed. with permission from the IESNA.)

The bulbs of some fluorescent lamps have a single, thick inner coat of conventional “halophosphor.” Adding a thin coat of more expensive, rare-earth triphosphors can provide an improved color rendering index (CRI) and increase the efficacy. When a double coat of the triphosphors is used, CRIs are 80 to 90, while retaining the higher levels of lumens per watt. Triphosphor coatings are standard on certain families of fluorescent lamps—check manufactures’ technical literature for current information, and for designations employed with superior-color lamps. Special phosphors are also used in fluorescent lamps designed for plant growth and for black-light effects.

Bases. Lamps designed for instant-start operation generally have a base at each end with a single pin connection. (In some cases instant-start lamps may have two pins at each end electrically connected.) Lamps for preheat or rapid-start operation also have a base at each end, but with two pins (connections) in each. Some manufacturers use a green base finish or print to identify fluorescent lamps which have less mercury and/or pass the toxicity characteristic leaching procedure (TCLP), and therefore are classified as nonhazardous waste in many states. Rapid-start high-output lamps have recessed double-contact bases, and T-2 subminiature fluorescent lamps have axial bases. The circline lamp has a single four-pin connector. Compact fluorescent lamps may have single two-pin or four-pin bases. Four-pin bases are required if the lamps are to be dimmed. See Fig. 26-10 for images of the available fluorescent lamp base types.

Compact Fluorescent Lamps. Energy-conservation activities have focused attention on the relatively low efficacy and short life of general-service 25- to 100-W incandescent lamps widely used in many residential, commercial, institutional, and industrial applications. Compact fluorescent lamps provide significantly higher efficacy and come in a variety of sizes and wattages (see Table 26-9). Shorter models can replace incandescent lamps in existing and new table and floor lamps, in recessed downlights, etc. The 10¹/₂- and 22¹/₂-in-long sizes are useful in 1- and 2-ft luminaires, and a three-lamp, 2 by 2 ft recessed luminaire with 40-W twin-tube lamps can achieve so-called “nondirectional” layouts without significant reduction in total luminaire output

TABLE 26-9 Typical “Compact” and Longer Twin Tube Fluorescent Lamps with Pin Bases

Watts	Generic lamp designation	Number of twin tubes	Bulb	Nominal length	Initial lumens
5	CFT5	1	T4	3.4	230
7	CFT7	1	T4	4.5	400
9	CFT9	1	T4	5.7	580
13	CFT13	1	T4	6.2	820
9	CFQ9	2	T4	4.3	560
10	CFQ10	2	T4	4.0	600
13	CFQ13	2	T4	5.2	860
18	CFQ18	2	T4	5.8	1160
26	CFQ26	2	T4	6.9	1700
13	CFTR13	3	T4	4.2	900
18	CFTR18	3	T4	4.4	1200
26	CFTR26	3	T4	5.0	1710
32	CFTR32	3	T4	5.6	2200
42	CFTR42	3	T4	6.4	3200
57	CFTR57	3	T4	7.8	4300
70	CFTR70	3	T4	9.3	5200
32	FT32	1	T4	5.8	2200
39	FT39	1	T5	16.5	2850
39	FT39	1	T5	22.5	3150
50	FT50	1	T5	22.5	4000

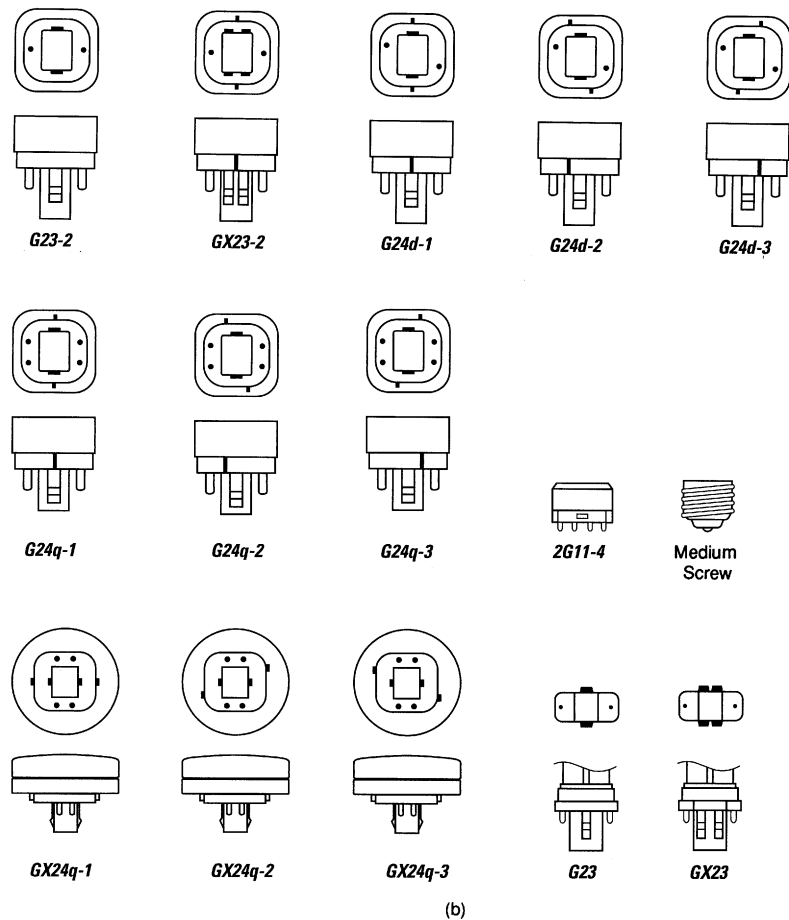
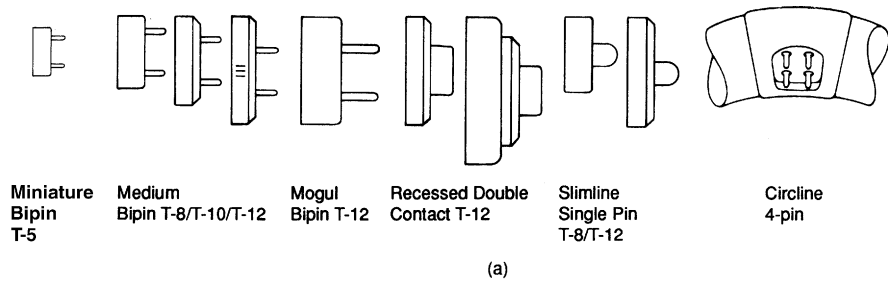


FIGURE 26-10 Base used for common types of fluorescent lamps: (a) regular fluorescent lamps bases, (b) compact fluorescent lamps bases.

compared with 2×4 ft units. Designers should check with lamp manufacturers about suitability for dimming.

Medium-screw base adapters are available for installing certain compact fluorescent lamps in 120-V as sockets. Some adapters have integral preheat ballasts, and others contain electronic components. Permanently assembled lamps, starter, and ballast units are also available with medium-screw bases.

Certain adapters can be used with bare compact fluorescent lamps, while other adapters have enclosing globes of various shapes, or reflectors to obtain directional light. Typical input wattages are 5, 9, 13, 18, and 26, considered as replacements for 25-, 40-, 60-, 75-, and 100-W incandescent lamps, respectively.

Energy Distribution. The approximate distribution of energy in a typical cool white fluorescent lamps is shown in Fig. 26-11.

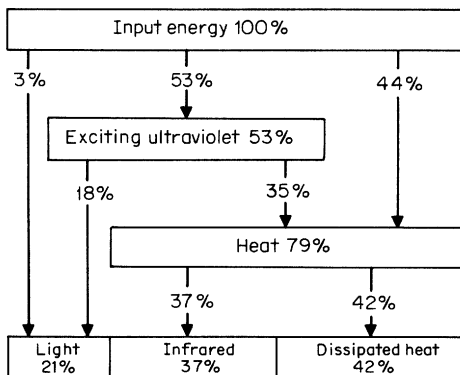


FIGURE 26-11 Energy distribution in a typical fluorescent lamp.

Performance Characteristics. Table 26-8 lists some typical fluorescent lamps for general lighting along with their physical characteristics, rated life, color-rendering index, and rated initial lumen output. Consult ballast manufacturers for input wattage data needed for energy calculations. Table 26-10, contains data for a variety of fluorescent lamp/ballast combinations. Due to the significant savings provided by electronic ballasts, most fluorescent ballasts used today in commercial luminaires are electronic.

The escalation of electronic data-processing equipment and variable-speed motors increased attention given to the harmonic content of electric power systems. Fluorescent-lamp ballasts are known to contribute to total harmonic distortion (THD). Harmonics raise the current in the neutral conductor of 3-phase, 4-wire, wye-connected power distribution systems, even though the phase loads may be reasonably balanced. Some older circuits exist where reduced neutrals are used for fluorescent lighting loads. However, full 100%

TABLE 26-10 Wattage and Efficacy Data for a Variety of Fluorescent Lamp/Ballast Combinations

Lamp designation	Lumens	Lamp wattage	Nominal length in	Ballast type	Ballast factor	Single-lamp ballast input watts	Two-lamp ballast input watts	Efficacy
F34T12		34	48	Electronic	0.9	30	59	
F34T12		34	48	Magnetic	0.91/0.89	44	77	
F40T12		40	48	Electronic	0.88/0.84	38	69	
F17T8		17	24	Electronic	0.95/0.98	19	34	
F32T8		32	48	Electronic	1.2		78	
F32T8		32	48	Electronic	0.88		59	
F54T5HO		54	46	Electronic	1	62/60	121/118	
F96T12		75	96	Electronic	0.88		135	
F96T12HO		110	96	Electronic	0.88		210	
F96T8		86	96	Electronic	0.88		112/110	
FT40		40	22.6	Electronic	0.88	38/37	76/73	

capacity neutral conductors have long been recommended for branch circuits serving loads consisting of more than one-half fluorescent lighting. Indeed, some electrical engineers specify cables with single, oversized neutral conductors, cables providing a separate neutral for each phase, transformers designed to handle harmonic loading, etc.

Light output for fluorescent lamps is sensitive to surrounding (ambient) air temperature as shown in Fig. 26-12. Lamp wattage changes in a similar fashion, but not as drastically at ambients below normal. Lamps operated at ambient temperatures below 60°F should be enclosed to conserve their heat. Air movement over the lamp bulb has the effect of lowered ambient temperature. Some CFLs apply a mercury amalgam that provides more stable lumen output over a wider range of temperatures and operating positions.

Fluorescent lamps generally should be operated at voltages within $\pm 10\%$ of their designed operating points for best performance. Decreased life and uncertain starting may result from operation at lower voltages, and at higher voltages there is danger of overheating of the ballast as well as decreased lamp life. One exception to this is found in the series operation of cold-cathode lamps, where an adjustable voltage supply makes possible operation over a wide range of illumination levels, that is, dimmer operation such as that used in stage lighting.

Failure of a hot-cathode fluorescent lamp usually results from loss of active material from the cathode or cathodes. This loss proceeds gradually throughout the life of the lamp and is accelerated by frequent starting. Depreciation of light output is caused principally by tube blackening and is rapid (as much as 10%) during the first 100 h but very gradual from that point on. For this reason the lamps are rated commercially on the basis of the lumen output after 100 h of operation.

Fluorescent-lamp Operation. Fluorescent lamps are best adapted to operate on ac circuits with reactance ballasts. Typical operating circuits are shown in Figs. 26-13 to 26-17.

Fluorescent lamps are, to a considerable extent, dependent on the characteristics of the ballast equipment. Typical of this is the effect of variations from rated line voltage on the conditions of lamp operation. Certified ballasts made in accordance with industry specifications and periodically field-checked by an independent laboratory are available for the more commonly used fluorescent lamps. They are to be distinguished by the letters CBM on the ballast case. Thermally protected “Class P” ballasts are required for fluorescent fixtures installed indoors, except fixtures with simple reactance ballasts.

The fluorescent lamps, in itself, is inherently a high-power-factor circuit, but the reactive ballast normally used to stabilize the arc is inherently low power factor. Since in the usual circuit the voltage drop across the ballast is approximately equal to that across the lamp arc, the resulting power factor of a single-lamp reactive-ballast circuit is on the order of 50%. For many applications this low power factor is objectionable. In single-lamp ballasts, power factor correction may be obtained by means of a capacitor shunted across the line connections or, where the

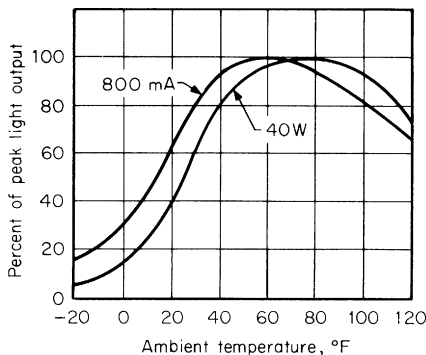


FIGURE 26-12 Effect of air temperature on light output for a typical fluorescent lamp

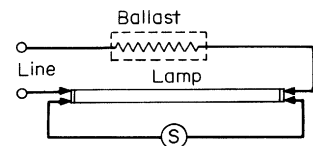


FIGURE 26-13 Single-lamp ballast for 4- to 40-W hot-cathode, preheat-starting fluorescent lamp (S = starting switch).

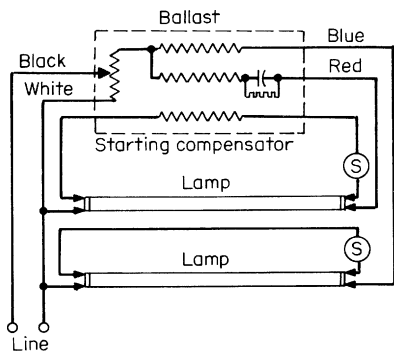


FIGURE 26-14 Two-lamp ballast circuit for 30- and 40-W hot cathode, preheat-starting fluorescent lamps, showing built-in starting compensator.

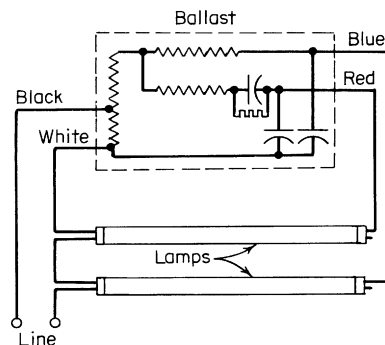


FIGURE 26-15 Two-lamp lead-lag ballast circuit for instant-starting hot-cathode lamps.

lamp requires a higher voltage, by a capacitor across the transformer secondary. The two-lamp ballast, through phase displacement of the lamp currents, or series capacitors, offers a ready means of power factor correction and is usually designed to give a circuit power factor greater than 90%.

All inductive fluorescent ballasts emit a certain amount of noise; the noise increases with the lamp current. A sound rating for ballasts has been developed by some manufacturers from A (quietest) to F (noisiest). The amount of cumulative ballast noise, which is tolerable, depends on two sets of principal factors: (1) characteristics of the room and (2) characteristics of the luminaire. Electronic ballasts are generally much quieter than magnetic ballasts and provide an "A" rating.

Where direct current is available at circuit voltages comparable with the open-circuit voltages of the usual ac ballast circuits, fluorescent lamps may be operated from these sources. For such operation, resistance must be added to the usual series reactance ballast (transformer ballasts are not applicable) to limit the operating current to the designed value. This causes a marked reduction in the overall efficacy of the lamp and circuit combination over that obtained in ac operation. Under dc operation, lamps more than a few feet in length will promptly develop a concentration of the mercury vapor at the negative end of the lamps, with the result that only a fraction of the bulb will give

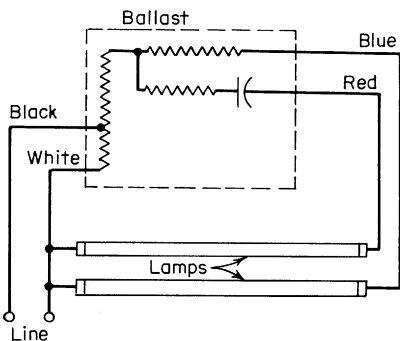


FIGURE 26-16 Two-lamp lead-lag ballast circuit for multiple operation of cold-cathode lamps.

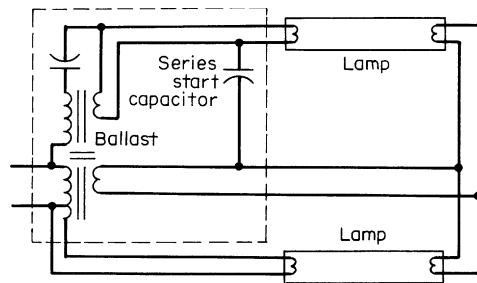


FIGURE 26-17 Two-lamp series rapid-start high-power-factor circuit.

off light. This condition can be overcome through a periodic (about once in 4 h) reversal of the polarity of the lines feeding the lamps. The life of lamps is likely to be shorter on dc.

Dimming. For dimming hot-cathode fluorescent lamps, a number of different arrangements are available. For smooth operation, the lamps on any circuit should be made by the same manufacturer, at the same time, in the same color, and of the same age in use. Group replacement is the most satisfactory procedure. Lamps should be operated free from drafts at 50 to 80°F and should be seasoned 100 h at full brightness prior to dimming. Certain energy-saving lamps are not recommended for dimming applications. Special dimming ballasts are typically required.

Dimming ballasts are available to reduce light output of T-8 and T-12 rapid-start lamps to 1%, 5%, or 10% of full lighting output. Most dimming ballasts are electronic ballasts. Standard T5 lamps can only be dimmed to 5% while T5HO can be dimmed to 1%. Compact fluorescent lamps can be dimmed to either 1% or 5%. Dimming ballasts offer slightly lower lumens per watt than nondimming electronic ballasts. One manufacturer states that dimming from 100% to 1% and to 10% is perceived as 10% and 32% of full brightness, respectively. Various sliding and other types of wall box and wireless dimmer controls are available for dimming control, or in connection with occupant and daylight sensors for automatic energy-conservation systems. Ballasts can be controlled via analog or digital signals, and the controller must be configured to operate the type of ballasts being used. Compatibility with emergency-lighting ballasts should also be explored.

Electronic Ballasts. The use of solid-state electronic elements instead of magnetic components can increase lamp efficacy by higher-frequency operation of lamps, and can reduce input power. This has made electronic ballasts the standard for today's fluorescent lighting systems. Some use a control chip that results in constant light output and energy consumption over a significant range of line voltages. Electronic ballasts are lighter in weight, operate cooler, and can be designed for rapid-and instant-start lamps to meet federal efficacy and FCC EMI/RFI standards. Some models permit dimming of fluorescent lamps, and can be used with appropriate sensors to compensate for changes in daylight illuminance levels. Electronic ballasts cost more than electromagnetic types, but often provide swift payback for the lighting-hours usage and kilowatt-hour rates typical of commercial, institutional, and industrial applications.

Table 26-11 shows the energy-saving potential of electronic ballasts. The annual operating cost values can be adjusted for burning hours other than 4000 h per year, and for kilowatt-hour rates lower or higher than 7 cents. Note that the combination of T-8 lamps and electronic ballasts gives higher system efficacy than other lamp-ballast combinations in the table. Ballast factor is the lumen output of lamps operated on commercial ballasts divided by the lumen output of those lamps operated on a reference ballast.

CBM electronic ballasts have ballast factors of 0.85 or higher, compared with 0.925 to 0.95 for CBM magnetic ballasts. However, fluorescent lamps operate at lower bulb-wall temperatures on electronic ballasts, so a ballast factor of 0.85 will result in approximately the same light output when within enclosed luminaires, compared to magnetic ballasts.

Both electronic and magnetic ballasts generate harmonics in the line current. For electronic types, most modern fluorescent ballasts limit the total harmonic distortion to under 20% or under 10%, neither of which should create problematic current in the neutral conductor. Engineers should check the current ANSI and IEEE 519/587 standards. Reported measurements of compact fluorescent lamps and diode devices for use in incandescent-lamp sockets showed power factors in the 47% to 67% range, and total harmonic distortion (THD) greater than 100%.¹ Although electronic ballasts generally have lower THDs than do magnetic ballasts, check compliance with the requirement of most electric utilities that the THD of electronic ballasts be less than 20%.

Many electronic components are employed in assembling electronic ballasts. Their specific designs are considered proprietary, but Fig. 26-18 gives the block diagram for basic electronic ballasts for fluorescent lamps.*

*Provided by J. N. Lester, Osram/Sylvania, Inc, Beverly, Mass.

TABLE 26-11 Luminous and Electrical Characteristics of a Three-Lamp VDT-Type Recessed Luminaire Using Various Lamp and Ballast Combinations

Lamp	Ballast	Luminaire			Comparative			Annual* operating cost, \$
		Ballast factor	Efficiency	Watts input	Lumen output	Watts input, %	Lumen output, %	System efficacy, %
F40-T12ES 2650 lm	Magnetic ESB	0.88	0.674	117	5355	Base 100	Base 100	Base 100
F32-T8 2900 lm	Magnetic for F32-T8	0.94	0.656	111	5362	95	100	120
F40-T12ES 2650	Electronic	0.82	0.668	88	4352	75	81	123
F32-T8 2900 lm	Electronic	0.93	0.719	90	6253	77	117	160

*Based on 4000 h at 7¢/kWh. Information furnished by Thomas Industries, Inc. Check manufacturers' technical literature, as data change frequently.
Formulas used:

$$\text{Annual operating cost} = W \times h / \text{year} \times \frac{\text{cost/kWh}}{1000}$$

$$\text{System efficacy} = \frac{\text{basic fixture efficiency} \times \text{lamp lumens} \times \text{ballast factor}}{\text{input watts}}$$

$$\text{Simple payback (in years)} = \frac{\text{additional cost}}{\text{savings / year}}$$

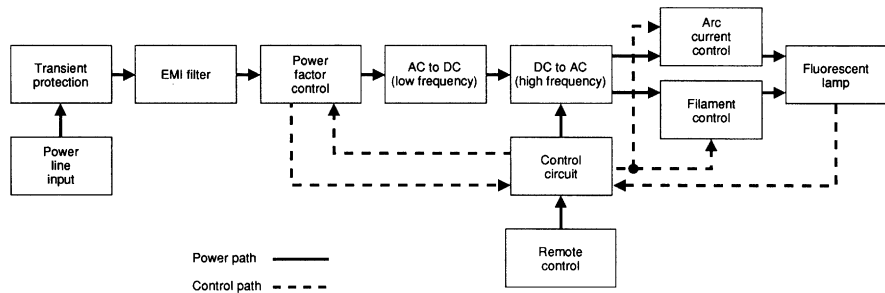


FIGURE 26-18 Basic block diagram for electronic fluorescent lamp ballasts. (Courtesy by Osram/Sylvania Inc.)

Most ballasts for T-2, T-4 and T-5 fluorescent lamps sense deactivated-cathode “end-of lamp life” conditions when one or more of the cathodes are depleted. This avoids a potentially hazardous situation when those small-diameter lamps are used with electronic ballasts, which could continue operating a bad-cathode lamp, perhaps causing the glass at that end to melt or crack. Some electronic ballasts for T-8 rapid-start lamps are expected to also incorporate end-of-life shutdown circuits.

Electronic ballasts are classified as rapid-start, instant-start, and programmed start. The latter designation is used for ballasts that contain a microprocessor programmed to preheat the cathodes and increase the starting voltage at an optimum temperature, and to sense end-of-lamp life and disconnect the ballast until the lamp is replaced.

Electronic instant-start ballasts give shorter lamp life than do rapid-start and programmed-start ballasts, but are lower in input wattage. The savings in kilowatt-hours often makes instant-start electronic ballasts the economic choice, unless occupancy sensors (or other causes of frequent lamp cycling) turn the lighting off and on 7 or more times each day. Users should also check with electronic ballast manufacture about level of line inrush current on starting.

26.5 HIGH-INTENSITY DISCHARGE LAMPS

High-Intensity Discharge (HID). This term denotes a general group of lamps consisting of mercury, metal halide, and high-pressure sodium lamps. A mercury lamp is an electric discharge lamp in which the major portion of the radiation is produced by the excitation of mercury atoms. A metal halide lamp is an electric discharge lamp in which the light is produced by the radiation from an excited mixture of a metallic vapor (mercury) and the products of the dissociation of halides (for example, halides of thallium, indium, sodium). A high-pressure sodium lamp is an electric discharge lamp in which the radiation is produced by the excitation of sodium vapor in which the partial pressure of the vapor during operation is of the order of 10^4 N/m².

Lamp Construction and Designation. HID lamps consist of a cylindrical transparent or translucent arc tube which confines the electric discharge and the associated gases. That tube is further enclosed in a glass bulb or outer jacket to exclude air to prevent oxidation of the metal parts and to stabilize operating temperatures and significantly reduce ultraviolet radiation emitted by the excitation of the vapors. The mount structure of many HID lamps is anchored to the “dimple top” of the outer glass bulb, assuring greater structural integrity and more accurate alignment of the arc tube. The construction of a typical mercury lamp is shown in Fig. 26-19. The basic elements are the arc tube, fabricated from fused silica and filled with a drop of mercury and a rare gas at low pressure; the electrodes; and the outer envelope, which may or may not have a phosphor coating on the

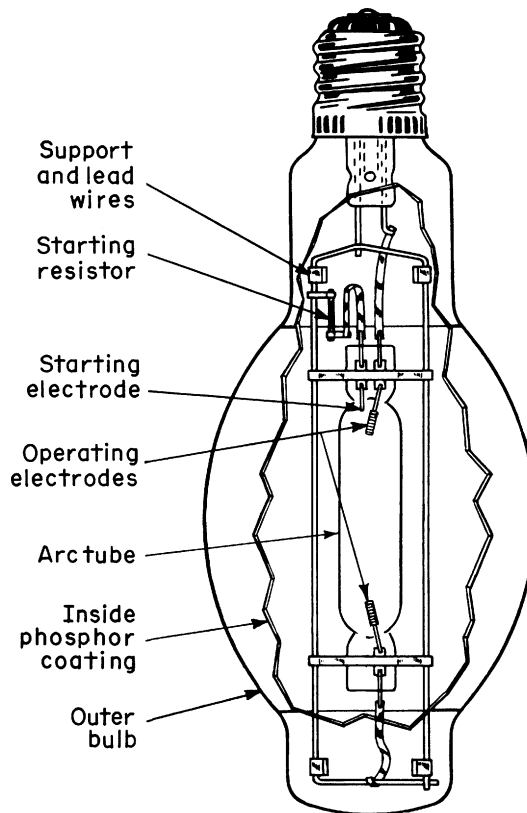


FIGURE 26-19 A 400-W phosphor-coated mercury lamp. Lamps of other sizes are constructed similarly.

interior for improved color rendering. Mercury lamps, due to their relative inefficiency and generally poor color rendering, are rarely, if ever, applied in today's lighting designs.

Metal halide lamps are very similar in construction to the mercury lamp, the major difference being the addition of a metal halide in the arc tube (see Fig. 26-20). The outer bulb may or may not have an inner phosphor coating to improve color rendition, and for lower, more uniform lamp brightness. Special metal halide lamps, with aluminized reflective coatings on the top of the bulb, can reduce glare and help minimize light trespass. There are PAR- and R-bulb mercury and metal halide lamps, xenon metal halide for fiber optic systems, and iodine metal halide to simulate natural daylight.

Metal Halide lamps have historically been susceptible to color maintenance problems due to shifts in their color over time. Recent developments aimed to minimize the occurrence of this problem include special rounded-shape arc tubes, pulse start ignitor technology, and the use of ceramic arc tubes.

The construction of a typical high-pressure sodium lamp is shown in Fig. 26-21. The basic components are the arc tube of translucent polycrystalline or single-crystal alumina, filled with sodium, mercury, and a rare gas (xenon); electrodes; and an outer borosilicate glass envelope. This outer bulb is either clear or contains an inner diffuse coating for more uniform lamp brightness. HPS lamps with twin arc tubes provide quick-restarting when momentary power failures occur. Rated at 40,000-h life, they also are valuable for difficult-to-reach locations.

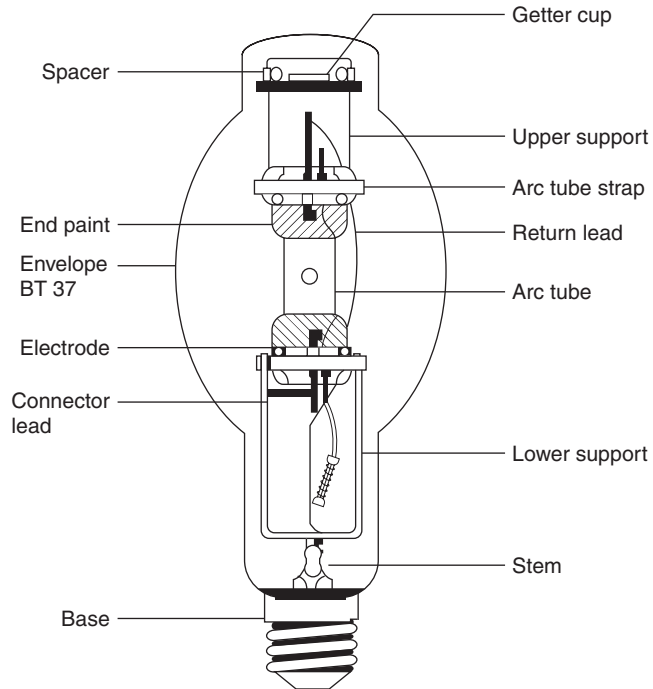


FIGURE 26-20 Construction of a standard metal halide lamp. (Courtesy of Osram Sylvania.)

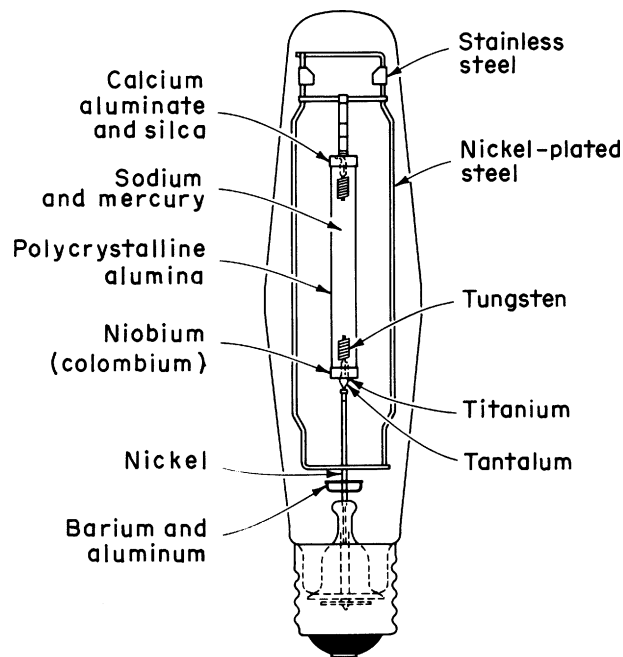


FIGURE 26-21 Construction of a typical high-pressure sodium lamp.

A lamp designation system developed by the American National standards Institute (ANSI) is currently in use.¹ It consists of five groups of letters or numbers: first a letter indicating the type of lamp (H, mercury; M, metal halide; S, high-pressure sodium), followed by an arbitrary number designating electrical characteristics (which relates to the type of ballast required), followed by two arbitrary letters which describe the physical characteristics, then the lamp nominal wattage, and finally letters indicating the phosphor color. An example for a 175-W metal halide lamp would be M57/C/175/U/MED.

Lamp Characteristics. Light output from each of the three types of HID lamps has its own color appearance (chromaticity), and the spectral power distributions vary as shown as in Fig. 26-22. Table 26-12 lists the radiated energy of typical 400-W HID lamps.

Performance Characteristics. Table 26-13 lists some typical metal halide and high-pressure sodium HID lamps for general lighting along with their light output (reference initial and mean lumens). The basis for published data may vary with manufacturer. For a qualitative comparison of HID lamps with incandescent and fluorescent lamps, see Table 26-14.

Many mercury and high-pressure sodium lamps, and some metal halide lamps, can be operated in any position. Other metal halide lamps have restricted narrow ranges of acceptable burning positions, outside of which light output and rated life may be adversely affected. Some metal halide lamps must be used only in enclosed luminaires, or may operate at higher temperatures which would exceed the temperature rating of explosion-proof or other hazardous-area luminaires. Certain metal halide lamps have compact outer bulbs and bases at each end, for smaller display-, sports- and flood-lighting luminaires. Some HID lamps have sufficient ultraviolet output to produce skin burn and/or eye injury, thus requiring specialized luminaires equipped with safety interlocks.

A new family of pulse-start metal halide lamps resulted from studies showing that improved lumen maintenance and color stability of metal halide lamps could result from (1) reducing the

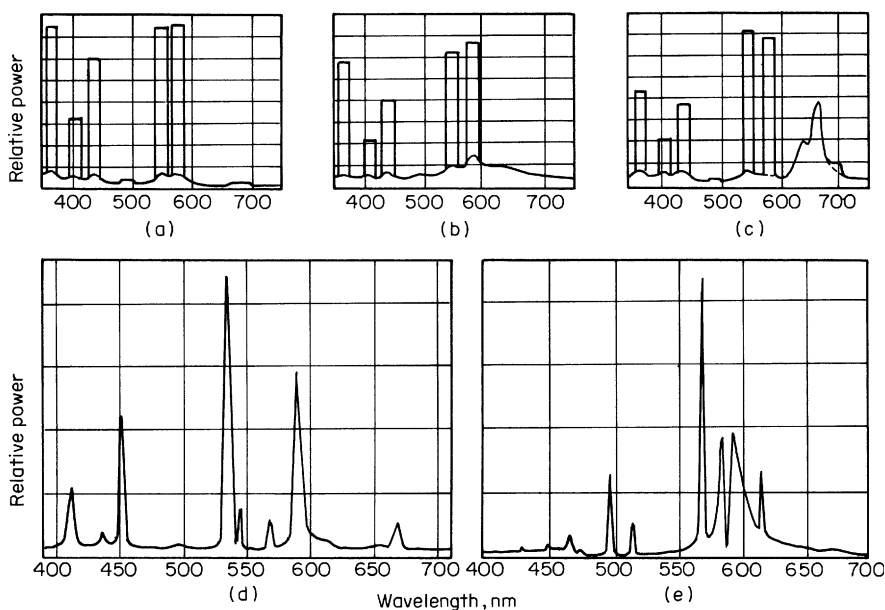


FIGURE 26-22 Spectral distribution curves for typical HID lamps: (a) clear mercury, (b) phosphor-coated mercury, (c) improved phosphor-coated mercury, (d) sodium-thallium-indium iodide metal halide, (e) high-pressure sodium.

TABLE 26-12 Energy Output for Some HID Lamps

Type of energy	400-W Mercury	400-W metal halide	400-W high Pressure sodium
Light	14.6%	20.6%	25.5%
Infrared	46.4	31.9	37.2
Ultraviolet	1.9	2.7	0.2
Conduction-convection	27.0	31.1	22.2
Ballast	10.1	13.7	14.9

sputtering of tungsten from the electrodes and (2) shortening the starting time.² Pulse start metal halide lamps require an ignitor with the proper ballast, and provide increased light output, longer life, quicker warmup, and faster hot restrike as additional benefits.

Another relatively new technology is that of ceramic arc-tube metal-halide lamps. These lamps are generally available in the lower wattages, some in PAR shapes, and provide improved color consistency and very good color rendering. The clear arc tube is replaced with a short translucent ceramic arc tube of similar material to that used in a high-pressure sodium lamp.

HID Lamp Operation. The practical limit of an HID lamp's current-carrying capacity is how high a temperature its enclosing tube can withstand without rupturing. By connecting an impedance in series with the lamp, the current is controlled. In most lamps about one-half the supply voltage is absorbed by a series ballasting device. A variety of ballasts are available for operating lamps, singly or in pairs. Single lamp ballasts may have low (0.50 minimum) or high (0.90 minimum) power factor, 2 lamp ballasts have inherently high power factor. The simplest lamp ballast is the reactor-type used in series with the lamp when line voltage is sufficient for reliable starting. This is not recommended where line-voltage fluctuations exceed 5%. A reactor-type ballast can be used when the line voltage is approximately twice the rated lamp voltage. The autotransformer-type ballast is used on circuits where the line voltage must be changed to suit the lamp requirements. Constant-wattage types of the autotransformer or isolated-secondary design are widely used because of better regulation, low line starting currents, and lower dropout voltage. They are also called *stabilized* or *regulated*. Heavier wiring, oversized circuit breakers, and time-delay relays that may be required by the relatively high starting currents of non-CW and non-CWA ballasts are eliminated with stabilizing ballasts, as the starting current is less than the rated operating current.

One of the limitations of the HID lamp is the effect of power-supply interruptions. In the event of a power interruption or voltage dip lasting for more than 1 cycle, HID lamps extinguish and do not restart for several minutes. The exact magnitude of the voltage drop to cause this condition depends on the ballast design. Regulator ballasts withstand a greater drop than other types. The delay in lamp restarting is caused by the high pressure that develops in the arc tube during operation. The open-circuit voltage of standard ballasts is not sufficient to restart the lamp until the lamp cools and the pressure decreases. In installations where this characteristic might be a safety hazard, the use of a few incandescent or fluorescent luminaires along with the HID units assures emergency illumination until the HID lamps restart. Tungsten-halogen auxiliaries are available for HID industrial luminaires to provide standby illumination in the event of momentary power failure. For indoor and outdoor sports lighting, and other applications where instant restrike is preferable, special ignitor are available, as are special instant-restrike high-pressure sodium lamps. Metal halide lamps with a wire lead (at the end opposite the base) are used with auxiliary ignitors to achieve instant restrike. For aisle lighting in warehouses and other interior and exterior situations where illumination levels for accurate seeing are not needed all of the time, high/low electrical components, combined with occupancy detectors, transmitters, and luminaire-mounted receiver scan provide major energy saving by reducing input wattage 50% to 70% during intervals when the spaces are unoccupied.

26-30 SECTION TWENTY-SIX

TABLE 26-13 Metal Halide and High-Pressure Sodium Hid Lamps^a

Watts	ANSI ballast type	Bulb	Bulb finish	Base	Maximum overall length, in	Vertical burning rated life, h	Initial	Mean	CRI
Pulse-start metal halide—vertically base up $\pm 15^\circ$									
32	M100	ED-17	Coated	Med	5.43	10,000	2,400	1,700	70
50	M100	ED-17 or BD-17	Clear	Med	5.43	10,000	3,900	3,200	70
70	M98	ED-17 or BD-17	Clear	Med	5.43	12,000	5,500	3,500	70
100	M90	ED-17 or BD-17	Clear	Med	5.43	15,000	9,000	6,200	70
150	M102	ED-17 or BD-17	Clear	Med	5.43	15,000	12,500	8,600	70
175	M137	BD-17 ED23.5	Clear	Mog	5.75 7.5	15,000	17,000	12,500	65 75
250	M138	ED-28	Clear	Mog	8.31	20,000	23,000	17,000	65
350	M131	ED-37	Clear	Mog	11.5	20,000	37,000	27,500	65
400	M135	ED-37	Clear	Mog	11.5	20,000	44,000	28,500	65
1000	M141	BT-37	Clear	Mog					
Ceramic MH									
39	M130	T4.5 T6	Clear	G	-	9,000	3,300	2,640	82
50	M110	ED-17	Clear	Med	5.43	10,000	4,100	2,750	85
70	M98	ED	Clear	Med	5.43	16,000	6,200	4,585	85
100	M90	ED	Clear	Med	5.43	16,000	9,500	7,125	85
150	M102	ED	Clear	Med	5.43	10,000	14,000	10,500	85
Ceramic MH PAR lamps									
39	M130	PAR20	SP 10 FL 30	Med	22,000 5,000	9,000	2,000	-	85
39	M130	PAR30L	SP 10 FL 30	Med	39,600 7,400	9,000	2,000	-	85
70	M98	PAR30L N	SP 12 FL 30	Med	46,000 13,200	9,000	4,400	-	85
70	M98	PAR38	SP 15 FL 25 WFL6 5	Med	40,000 16,000 3,500	10,000	4,300	-	85
100	M90	PAR38	SP 15 FL 25 WFL6 5	Med Skt	45,000 25,000 12,000	12,000	6,500	-	85
Metal halide—except as noted, vertically base up or base down $\pm 15^\circ$									
175	M57	BD-17 ED-28	Clear	Mog	8.25	10,000	13,500	9,100	
250	M58	ED-28	Clear	Mog	8.25	10,000	20,500	13,500	
400	M59	ED-28 ED-37	Clear	Mog	11.3	20,000	36,000	23,500	
400	M59	ED-28 ED-37	Coated	Mog	11.3	20,000	36,000	22,500	
1000	M47	BT-36 BT-56	Clear	Mog	11.3	12,000	11,000 0	71,000	
35	S76	B-17	Clear	Medium		16,000	2,250	2,025	22
50	S68	B-17 or ED-17	Clear	Medium		24,000+	4,000	3,600	22
70	S62	B17 or ED-231/2	Clear	Mogul	73/4	24,000+	6,400	5,450	22

TABLE 26-13 Metal Halide and High-Pressure Sodium Hid Lamps^a (Continued)

Watts	ANSI ballast type	Bulb	Bulb finish	Base	Maximum overall length, in	Vertical burning rated life, h	Initial	Mean	CRI
High Pressure Sodium Lamps—any burning position									
100	S54	B17 or ED-231/2	Clear	Mogul	73/4	24,000+	9,500	8,550	22
150	S55	B17 or ED-231/2	Clear	Mogul	73/4	24,000+	16,000	14,400	22
200	S66	ED-18	Clear	Mogul	93/4	24,000+	22,000	19,800	22
250	S50	ED-18	Clear	Mogul	93/4	24,000+	28,000	27,000	22
310	S67	ED-18	Clear	Mogul	93/4	24,000+	37,000	33,300	22
400	S51	ED-18	Clear	Mogul	93/4	24,000+	51,000	45,000	22
400	S51	ED-37	Diffuse	Mogul	11	24,000+	47,500	42,750	22
1000	S52	E-25	Clear	Mogul		24,000+	140,000	126,000	22

^aConsult manufacturers' technical literature for current data, as values and types change frequently.

^bInitial—after 100 h of burning; mean—for mercury and HPS at 50% of rated life, and for metal halide lamps, at 40% of rated life.

^cColor rendering index.

^dCheck manufacturer's literature. May require enclosed luminaire.

TABLE 26-14 Advantages and Disadvantages of the Different Lamp Types

Light source	Advantages	Disadvantages
Incandescent general-service	Compact size, no ballast, good optical control, good color rendering, low first cost, dimmable, good lumen maintenance	Short life, low efficacy, radiant-heat effects
Tungsten-halogen incandescent	Compact, no ballast, good color rendering, moderate life, excellent optical control, dimmable, excellent lumen maintenance	Lamp handling is difficult during maintenance, high cost low efficacy, radiant-heat effects, operating temperature affects lamp life
Fluorescent	Linear shape, moderate cost, high efficacy long life, good lumen maintenance dimmable, rare-earth phosphors can give excellent color rendering	Ballast needed, optical control limited, ballasts may be noisy, ambient temperature affects light output and color
Improved-color mercury (HID) (Rarely used today)	Moderate efficacy, very long life, good lumen maintenance, burning position not critical, limited dimming range lamp and ballast	Starting takes 5–7 min, does not restart immediately, ballasts needed are large and may be noisy, relatively high cost of
Metal halide (HID)	High efficacy, good color rendering, medium life, good optional control, limited dimming range	Variations in color, burn position very important, does not restart immediately, ballasts large and may be noisy, high cost of lamp and ballast, starting takes 3–4 min
High-pressure sodium (HID)	Very high efficacy, long lamp life, excellent lumen maintenance, limited dimming range	Poor color rendering, does not restart immediately, ballasts large and may be noisy, high cost of lamp and ballast, starting takes 3–4 min, high luminance can cause control problems

REFERENCES ON HIGH-INTENSITY DISCHARGE LAMPS

1. ANSI, American National standard for Electric Lamps—High-Intensity Discharge Lamps, Method of Designation, C78.380-2005, American National Standards Institute, New York (also available at www.nema.org)
2. Nortrup, F., Kraska, Z., and Lou, S., Pulse Start of Metal Halide Lamps for Improved Lumen Maintenance, *J. Illum. Eng. Soc. N. Am.*, 1996, vol. 23, no. 2, pp. 113–116.

26.6 MISCELLANEOUS LAMPS

Low-Pressure Sodium Lamps. These are sodium vapor lamps in which the partial pressure of the vapor during operation does not exceed a few newtons per square meter. Their light output is almost monochromatic, consisting of a double line in the yellow region of the spectrum at 589 and 589.6 nm.

As with other electric discharge sources, a ballast is required. Starting time to full light output is 7 to 15 min, but the lamp will restart immediately after interruption of the power supply. The major application of these lamps is for area lighting and streetlighting where monochromatic yellow light is acceptable and a high luminous efficacy is required. Low-pressure sodium lamps are often applied in the vicinity of astronomical observatories, since the monochromatic light can be filtered out of telescope images.

Glow Lamps. When sufficient voltage is applied to electrodes sealed within a bulb containing neon, argon, or helium, light is produced at the negative electrode. On direct current, one cathode glows; on alternating current, the reversal is so rapid, both electrodes appear to glow. The range of glow lamps is 1/25 W to 3 W. Their useful life varies approximately as the inverse of the cube of the current. A glow lamp has a negative volt ampere characteristic; hence a limiting resistance is used in series with it. In conventional screw-base types, the resistor is concealed in the base. Average lamp life ranges between 7500 and 25,000 h.

Glow lamps have wide use in electronic circuitry, where their action is that of a practically instantaneous switch. At breakdown voltage, the lamp glows, and the switch is closed; at the extinguishing voltage, the lamp current drops to a fraction of its full value and may be considered as nonconducting, or open-circuit in certain circumstances. This on-off characteristic suits the glow lamp to the dichotomy of binary arithmetic as used in computers and logic circuitry in general. Other glow-lamp applications in electronic circuitry include oscillators, pulse generators, voltage regulators, and coupling networks.

Electroluminescent Lamps. This type of lamp is a thin-area source in which light is produced by a phosphor excited by a pulsating electric field. In essence, the lamp is a plate capacitor with a phosphor embedded in its dielectric and with one or both of its plates transparent. Green, blue, yellow, or white light may be produced by choice of phosphor. The green phosphor has the highest luminance. These lamps are available in ceramic and plastic form, are flexible or have a stiff backing, and are easily fabricated into simple or complex shapes. They have been used in decorative lighting, night lights, switchplates, instrument panels, clock faces, telephone dials, thermometers, and aircraft egress marking strips and signs. Their application is limited to locations where the general illumination is low.

Luminance varies with applied voltage, frequency, and temperature, as well as with the type of phosphor. Life is long and power consumption is low. There is no abrupt point at which the lamp fails; the time at which the luminance has fallen to 50% of initial is sometimes used as a measure of useful life. For the ceramic form, this is approximately 20,000 h at 120 V, 60 Hz. Approximate initial current and wattage values per square foot of lamp under these operating conditions are 60 mA and 3.5 W.

Black-Light Lamps.¹ Near-ultraviolet radiant energy (energy not visible to the human eye) causes certain materials to fluoresce or emit visible light. The normal human eye is sensitive only to radiant energy between 380 and 780 nm in wavelength. Thus, lamps that produce primarily near-ultraviolet radiant energy in the 320- and 380-nm range are popularly called *black lights*. This term

is quite descriptive, since the ultraviolet energy from the light source cannot be seen by the human eye, but the effects of the radiation on special materials can be visually dramatic.

When black light is directed at a fluorescent material, an energy conversion takes place. The material or chemical sensitive to ultraviolet energy absorbs the energy, then reradiates it at longer wavelengths to which the eye is sensitive.

Mercury lamps with filters to absorb the visible light and transmit the near-ultraviolet are used for fluorescent effects. Called black-light lamps, they are generally enclosed in a red-purple filter glass bulb that looks black. Many materials fluoresce when irradiated by black-light lamps. They are used for theatrical and advertising effects, industrial and food inspection, detection of counterfeits and forgeries, medical diagnosis, insect traps, crime and vermin detection, laundry marking, and copying equipment.

Tubular sources designated as BLB lamps, such as 4-, 6-, and 8-W T-5, 15-W T-8, and 20- and 40-W T-12 lamps, have integral filters and may be operated with the same ballasts as corresponding fluorescent lamps.

The luminance of an irradiated fluorescent material is between 1 and 5 fL with printing inks and between 0.25 and 2.5 fL with interior paints, depending on the color. The apparent brightness increases considerably as the eyes become dark-adapted. Conversely, the effectiveness of black light is greatly reduced or entirely negated by a small amount of visible light.

Short-Arc Sources. Also called “compact arcs,” these lamps have glass-enclosed arcs in bulbs containing mercury-argon, mercury-xenon, and xenon, to give the high brightness of carbon arcs, but without their dirty operational and maintenance problems. Principal applications are display systems, optical instruments, projectors, and searchlights.

Sulfur Lamps. Brilliant white light can be produced by using kitchen-grade microwave energy to excite a small quantity of sulfur within an argon-filled quartz sphere of golf-ball size.* The small sphere must be rotated at 300 to 600 r/min to keep the quartz from melting. The light output is said to be 125,000 to 175,000 lumens, and the target efficacy is 110 to 140 lumens per watt, with target input power of 800 to 1200 W.

Induction Lighting Systems. The discharge bulb contains mercury and an inert gas, and the inner surface is coated with phosphor, giving 3000 or 4000 K white light. An axially located power coupler serves as an antenna to radiate 2.65-MHz energy received via coaxial cable from an external high-frequency generator. Light output from the 85 system watts: initial 6000 lumens, mean 4800 lumens, CRI 80+, and rated life 100,000 h. (*Note:* this is the principle used for the 23-W R-25 bulb compact fluorescent lamp listed in Table 26-12.)

REFERENCES ON MISCELLANEOUS LAMPS

1. Kraehenbuehl, J. O., and Chanon, H. J., Technology of Brightness Production by Near-Ultraviolet Radiation, *Trans. IES*, Feb. 1941.
2. Cook, H., Stretching the Spectrum, *Building Design and Construction*, June 1998.

26.7 LUMINAIRES AND LIGHTING SYSTEMS

Luminaires. These are complete lighting units consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply. They are clarified in the CIE.

*Fusion Lighting Inc. Rockville, Md. See also Cook.²

(International Commission on Illumination) according to the percentage of light output above and below the horizontal as follows:

Direct	0%–10% upward, 90%–100% downward
Semidirect	10%–40% upward, 60%–90% downward
General diffuse	40%–60% upward, 40%–60% downward
Semi-indirect	60%–90% upward, 10%–40% downward
Indirect	90%–100% upward, 0%–10% downward

This classification system applies to all types of luminaires for general lighting in industrial, commercial, and residential applications.

Lighting systems are installations of one or more luminaires and are classified in a number of different ways. One of these is by CIE distribution type, since these different distributions provide different lighting quality, performance and space appearance.

Direct Lighting. When luminaires direct 90% to 100% of their output downward, they form a direct lighting system. The distribution may vary from widespread to highly concentrating, depending on the reflector material, finish, and contour, and on the shielding or control media employed. Troffers and downlights are two forms of direct luminaires.

Direct lighting units can have the highest utilization of all types, but this utilization may be reduced in varying degrees by brightness-control media required to minimize direct glare. Veiling reflections and shadows may be excessive unless the distribution and location of luminaires are designed to reduce these effects. Large-area units are generally also advantageous since they soften shadows.

Luminous ceilings, louvered ceilings, and large-area modular lighting elements are forms of direct lighting having characteristics similar to those of indirect lighting discussed in paragraphs below. Luminous ceilings may be difficult to apply at low power densities.

Semidirect Lighting. The distribution from semidirect units is predominantly downward (60% to 90%) but with a small upward component to illuminate the ceiling and upper walls. The characteristics are essentially the same as for direct lighting except that the upward component will tend to soften shadows and improve room brightness. Care should be exercised with close-to ceiling mounting of some types to prevent overly bright ceilings directly above the luminaire. Utilization can approach, or even sometimes exceed, that of well-shielded direct units.

General Diffuse Lighting. When downward and upward components of light from surface-mounted and suspended luminaires are about equal (each 40% to 60% of total luminaire output), the system is classified as general diffuse. General-diffuse units combine the characteristics of direct lighting described above and those of indirect lighting described below. Utilization is somewhat lower than for direct or semidirect units, but it is still quite good in rooms with high-reflectance surfaces. Brightness relationships throughout the room are generally good, and shadows form the direct component are softened by the upward light reflected from the ceiling.

Direct-indirect is a special (non-CIE) category within this classification for luminaires which emit very little light at angles near the horizontal. Since this characteristic results in lower luminances in the direct-glare zone, direct-indirect luminaires are often more suitable than general-diffuse luminaires which distribute the light about equally in all directions, especially in spaces involving critical and prolonged seeing.

Semi-Indirect Lighting. Lighting systems which emit 60% to 90% of their output upward are defined as semi-indirect. The characteristics of semi-indirect lighting are similar to those of indirect systems discussed below except that the downward component usually produces a luminaire luminance that closely matches that of the ceiling. However, if the downward component becomes too great and is not properly controlled, direct or reflected glare may result.

Indirect Lighting. Lighting systems classified as indirect are those which direct 90% to 100% of the light upward to the ceiling and upper sidewalls. In a well-designed installation, the entire ceiling becomes the primary source of illumination, and shadows are virtually eliminated. Also, since the luminaires direct very little light downward, both direct and reflected glare will be minimized if the installation is well planned. Luminaires whose luminance approximates that of the ceiling have some advantages in this respect. It is also important to suspend the luminaires a sufficient distance below the ceiling to obtain reasonable uniformity of ceiling luminance without excessive luminance immediately above the luminaires.

Since with indirect lighting the ceiling and upper walls must reflect light to the work plane, it is essential that these surfaces have high diffuse reflectances, but low specular reflectances. Care is needed to prevent overall ceiling luminance from becoming too high and thus glaring.

Control of Light Distribution. This is usually accomplished through reflection, refraction, transmission, absorption, and diffusion using glasses, plastics, metals, and woods, of various shapes, reflectance, transmittance, absorptance, polarization, and finish. Reflector contour shapes include parabolic, ellipsoidal, hyperbolic, and spherical. Refractors (lenses) utilizing prisms, cones, and spherical shapes are commonly used to produce a wide range of light-controlling devices. Flat or contoured diffusers are used to diffuse, color, or polarize the light according to the lighting needs.

Lighting systems are also classified in accordance with their layout or location with respect to the visual task or object lighted—general lighting, localized general lighting, and local (supplementary) lighting.

General Lighting. Lighting systems that provide an approximately uniform level of illumination on the work plane over the entire area are called general lighting systems. The luminaires are usually arranged in a symmetrical plan fitted into the physical characteristics of the area and blend well with the room architecture. They are relatively simple to install and require no coordination with furniture or machinery that may not be in place at the time of the installation. Perhaps the greatest advantage of general lighting systems is that they permit complete flexibility in task location. Since they illuminate the entire space to the same level, they may provide more light than is necessary in certain parts of the room, and therefore consume more energy than needed.

Localized General Lighting. A localized general lighting system consists of a functional arrangement of luminaires with respect to the visual task or work areas. It also provides illumination for the entire room area. Such a lighting system requires special coordination in installation and careful consideration to ensure adequate general lighting for the room. This system has the advantages of better utilization of the light on the work area and the opportunity to locate the luminaires so that annoying shadows and direct and reflected glare are prevented.

Local Lighting. A local lighting system provides lighting only over a relatively small area occupied by the task and its immediate surround. The illumination may be from luminaires mounted near the task (task lighting) or from remote spotlights. It is an economical means of providing higher illumination levels over a small area, and it usually permits some adjustment of the lighting to suit the requirements of the individual. Improper adjustments may, however, cause annoying glare for nearby workers. Local lighting, by itself, is seldom desirable. To prevent excessive changes in adaptation, it should be used in conjunction with general lighting that is at least 20% of the local lighting level; it then becomes *supplementary lighting*. This combination of a local and general system is generally referred to as task-ambient lighting. Task ambient lighting can provide excellent energy efficiency because high illuminance levels are applied only where needed.

Application Considerations. There are many utilitarian, esthetic, energy-efficiency, and economic considerations that influence the selection of light sources, luminaires, and lighting system for interior spaces. The choices are simple for illuminating a janitorial closet, but increasingly difficult for areas requiring reasonably inconspicuous luminaires which provide the quantity and quality of light that enable rapid and accurate seeing of critical and prolonged visual tasks.

Changes in building design and escalating construction costs have combined to lower ceiling heights in typical commercial and institutional spaces. The expansion of computers and word processors containing visual display terminals (VDTs) brought many shiny, curved, near-vertical tasks of relatively low contrast into the visual environment. The parabolic troffer was for many years the lighting solution in office environments. The general environment provided by these luminaires often appears somewhat dark due to the low luminance of the ceiling plane. Appropriately configured pendant-mounted lighting systems with some amount of uplight generally provide higher quality office lighting, since these systems can both limit veiling reflections and provide higher overall space brightness.

Commercial and Institutional Interiors. In such spaces, the need exists to limit direct glare, reflected glare, and veiling reflections by selecting luminaires with appropriate luminous intensity distributions and finishes of furniture and room surfaces, as well as task reflectances, that provide appropriate illuminance levels and achieve luminance ratios within recommended limits (no greater than 3:1 or 1:3 for the task to the near surround and no more than 10:1 or 1:10 between the task and the far surround.)

As discussed above, a widely used luminaire type is the recessed troffer, with prismatic, parabola-shaped or other louvered enclosures. Standard sizes are 1 × 4 ft, 20 × 48 in, 2 × 2 ft, and 2 × 4 ft. The 3- and 4-in deep parabolic louvers are popular when critical and prolonged seeing tasks are involved, or where inconspicuous lighting systems are desired.

Pendant luminaires are available in a variety of distributions, shapes, and sizes. T8 lamps are the most common lamps in these luminaires, but the small diameter of T5 lamps generally provides for better optical control and permits smaller pendant luminaire cross sections.

Hard-metric* recessed luminaires are available as a result of the 1994 policy requiring them in future construction projects of all U.S. federal agencies. Later the 1996 Savings in Construction Act passed in the 105th Congress mandated that hard-metric luminaires must not be more costly than soft-metric† models.

Computer monitors are increasingly available with finishes that are less susceptible to reflected glare, and as a result, luminaires such as recessed direct-indirect troffers are being promoted by some manufacturers to provide environments with more vertical illuminance for walls and other surfaces. These large square or rectangular units, with all the components above the ceiling plane, contain shielded fluorescent-lamp luminaire elements positioned to direct all or most of the light to white-finished curved or sloping sides, but are actually a CIE direct luminaire distribution. The tendency of these recessed direct-indirect luminaires to produce direct or reflected glare is similar to that of lensed luminaires, and is a function of their luminance.

Specialized models of small- and large-cell parabolic louvers in recessed and surface-mounted luminaires are designed to meet standards of the Illuminating Engineering Society of North America for spaces with VDTs. Parabolic luminaires expected to be used with T-8, high-lumen compact, and other rare-earth phosphor fluorescent lamps should be equipped with low-iridescence aluminum louvers.

The National Electrical Manufacturers Association provides dimensions to help ensure compatibility with conventional generic systems for ceiling suspension. Dimensions are provided for a variety of different ceiling systems, along with cross-section details showing how the luminaires interface with the ceiling systems¹.

Combining Lighting and Air Conditioning. Families of recessed fluorescent-lamp luminaires (troffers) are designed to provide the additional function of bringing cool or warm air into interior spaces and to take air out of those spaces, thus eliminating or minimizing the need for supply air diffusers and return air grilles. The air-supply function is accomplished by slots along the bottom edge of the luminaire sides, above which sheet-metal air connectors (frequently called *airboots*—see Fig. 26-23a) spread out the conditioned air received by 5-, 6-, and 7-in flexible ducts form larger plenum ducts. Air connectors can be above one or both side slots, can be internally insulated or uninsulated,

*Hard-metric: even multiples of 100 mm (e.g., 600 × 1200 mm).

†Soft-metric: a simple conversion of inches to metric equivalents [e.g., 609.6 × 1219.2 mm (24 × 48 in)].

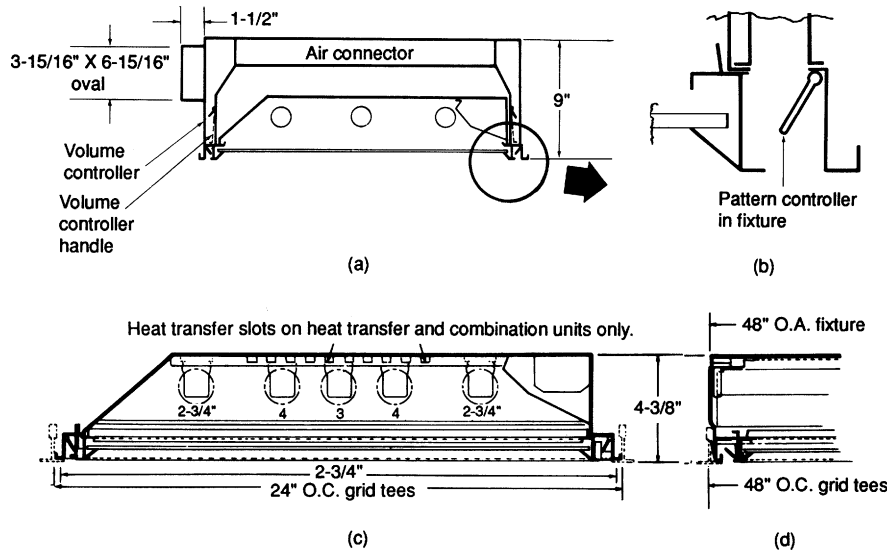


FIGURE 26-23 Typical cross sections and dimensions of (a) air connectors (boots), (b) air-supply pattern control blade, (c) cross, and (d) end views of air-handling supply and/or heat-transfer-recessed fluorescent luminaire.

and can have volume-control dampers. The luminaire side slots can include air pattern-control blades (Fig. 26-23b), which are field positioned to be closed (static), at 45° for horizontal air supply, and vertical (fully open) for vertical air supply. Side slots may also be used to return air to the plenum, or to connect directly to a ducted air return system.

Room air can also be pulled through the lamp compartment of troffers by creating negative air pressure in the plenum and building in suitable air entry and air exit openings in the luminaire. By this process, considerable lamp and ballast heat is then expelled through top openings into the plenum. Called *heat transfer* or *heat exhaust*, such luminaires can significantly reduce the heat sent into the occupied space below, increase light output because of the more optimum temperature inside the lamp compartment, and provide a thermal environment for more favorable ballast life.

Air-handling luminaires can combine both the air supply and heat-transfer return air functions, called *combination units* in Fig. 26-23c, which shows the top heat-transfer openings, and the two end openings (Fig. 26-23d), which allow room air to enter the lamp compartment.

Luminaire mounting issues. Incandescent- and HID-lamp luminaires for surface and recessed applications are widely used for downlighting, wall washing, etc. Surface or recessed track with suspended, adjustable incandescent luminaires is popular for display and localized lighting in stores, restaurants, art galleries, museums, etc. See the latest edition of the NEC for special requirements, such as thermal protection for incandescent and HID recessed luminaires, minimum clearances for clothes closets, and wattage and temperature markings.

Fluorescent-lamp luminaires designed for surface mounting are of the prismatic wraparound, metal-box, or bare-lamp (strip) types. If such luminaires are to be installed on combustible low-density cellulose fiberboard, they must be listed for that condition, or be spaced at least 1 1/2 in from the surface of the fiberboard.

Industrial Interiors. Luminaires with fluorescent lamps are often preferred for low-bay industrial spaces, generally involving mounting heights 12 ft or less above the floor. Eight-foot units with center-V reflectors and 96 in 800 mA “high output” lamps frequently produce lower overall cost of light than slimline and 1500-mA models, although the extra-high-output type normally results in

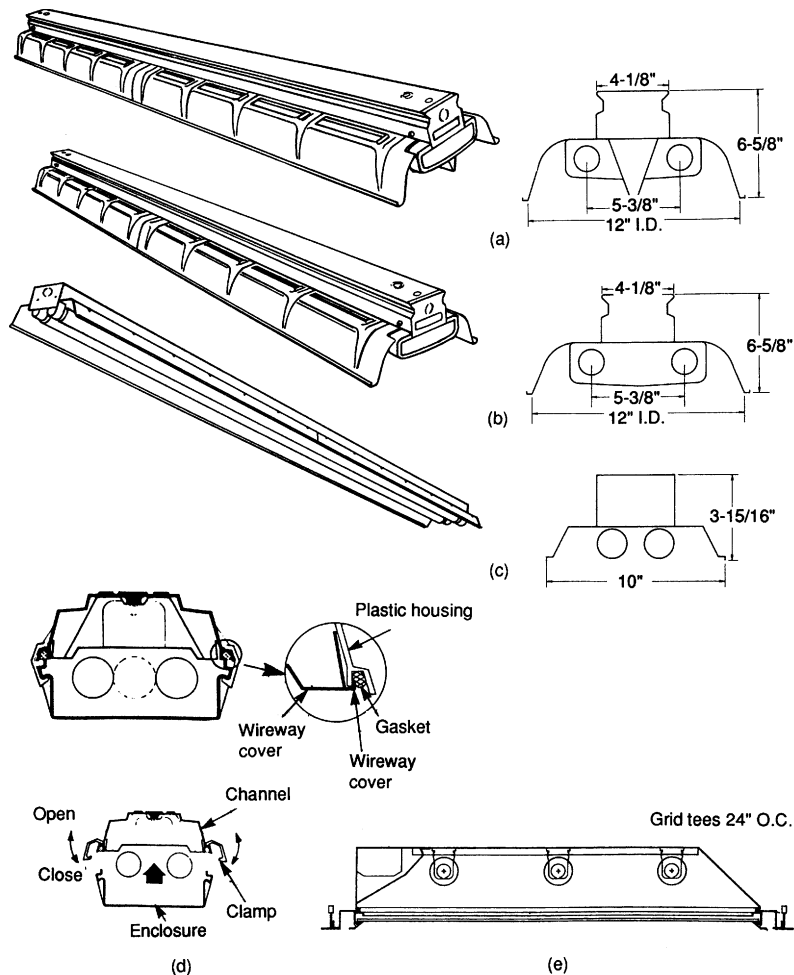


FIGURE 26-24 Industrial fluorescent-lamp luminaire types for nonhazardous areas.

most favorable initial cost. Units with four 4-ft lamps are popular with many plant engineers and maintenance supervisors because of the shorter bulb length. Figure 26-24 shows the wide top slots that give approximately 25% upward light, and the center-V providing greater reflector rigidity and 30° crosswise shielding, which improves visual comfort by reducing direct glare, especially when luminaires are oriented so the long dimension is at right angles to the predominant direction of the worker's line of sight (called *crosswise viewing*). Other models without center-V reflectors frequently have narrower top slots giving approximately 10% upward light and 13° crosswise shielding (Fig. 26-24b). Economical luminaires have more shallow 10% uplight or closed-top reflectors (Fig. 26-24c). Steel reflectors are most common, with porcelain-or baked-enamel finish.

T5 fluorescent lamps are also applied in industrial lighting where high output linear lamps can be grouped together in a single luminaire to provide sufficient light output for use in high bay applications where HID luminaires are typically applied. Traditional high-bay luminaires with round aluminum, glass, or acrylic reflectors (Fig. 26-25) are also available with multiple compact fluorescent lamps instead of HID lamps. These systems can provide multiple light levels through switching of

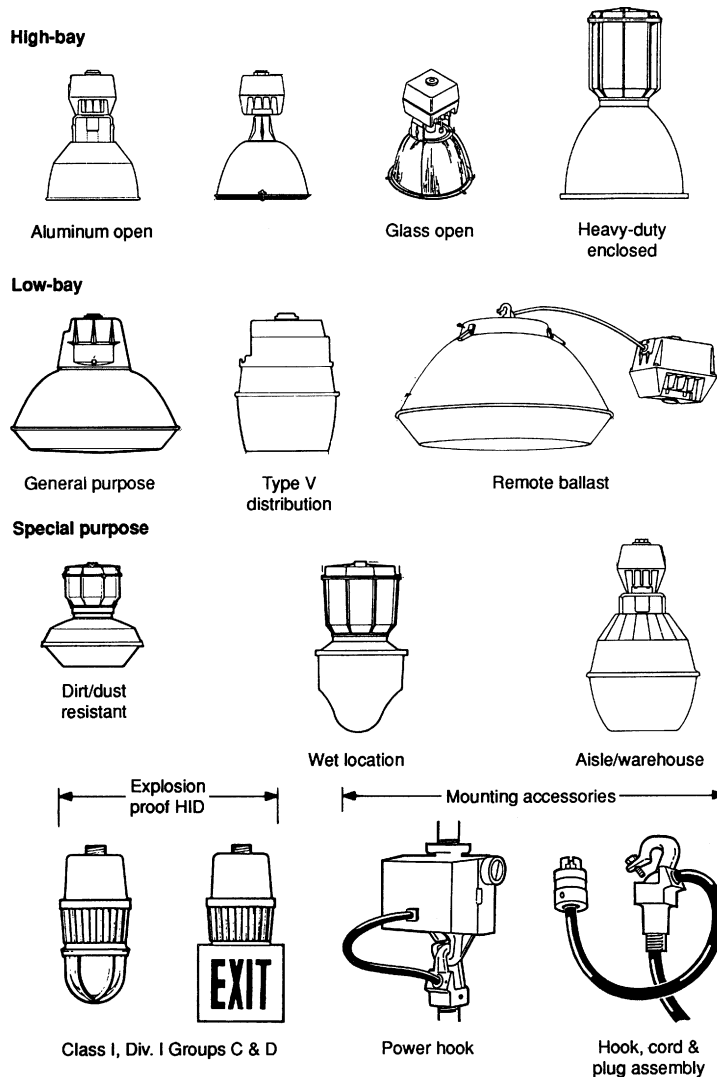


FIGURE 26-25 Industrial HID and incandescent lamp luminaire types and mounting accessories, and two explosion-proof models.

different groups of lamps in the same luminaire, and have been applied in warehouses, stores, gymnasiums and numerous other applications.

Specialized nonhazardous area industrial fluorescent luminaires include enclosed types for dirt- and moisture-resistant applications (Fig. 26-24d), recessed troffers for clean rooms (Fig. 26-24e), and compact fluorescent supplementary lighting units. Classifications of hazardous areas are defined in the NEC. Advice of the insurance carriers for the hazardous spaces involved is recommended to confirm appropriate classification before installing fluorescent, HID, or incandescent luminaires designed for hazardous areas.

Metal halide and high-pressure sodium industrial luminaires are prevalent for production, warehouse, and other industrial areas. Metal-halide lamps have color characteristics that are superior to

high-pressure sodium. High-pressure sodium systems generally result in more rapid payback for situations where minimum energy consumption is the goal and color rendition is an insignificant factor. However, the warm color of high-pressure sodium may be judged undesirable, especially if the visual tasks are such that the high-pressure sodium light would adversely affect seeing speed or accuracy. For example, workers may be less able to see small defects in brass and copper tasks, compared with other light sources.

Figure 26-25 shows typical HID industrial luminaires. High-bay units are generally for mounting heights of 18 ft or more above the floor, where cranes or maintenance catwalks simplify the task of relamping and reflector cleaning. Low-bay models are often selected when luminaires need to be positioned 13 to 18 ft above the floor, and periodic maintenance can be performed with portable scaffolding or lift trucks. Both the high- and low-bay types can employ remote ballasts. Integral or remote, the ballast must be suitable for the ambient temperature involved at the luminaire location.

A variety of HID luminaires are designed for specific purpose, and manufacturers provide mounting and wiring accessories that expedite installation and maintenance. Fuses (single for 120- and 277-V circuits, and double for 208, 240, and 480 V) can be located either in the ballast assembly or inside the power hook. Since regular HID lamps will not immediately restart after a momentary power interruption or a severe voltage dip, a tungsten halogen lamp inside the reflector can provide standby illumination for safety during the few minutes the high-pressure sodium or metal halide lamps are out. A "hot restrike" option is available for metal halide and high-pressure sodium systems. All HID ballasts produce some noise—for quieter operation of HID luminaires, encased and potted ballasts are available.

Merchandise and Display Lighting. Systems achieving the "3 A's" of store lighting (attraction, appraisal, and atmosphere) utilize many luminaire types to (1) call attention to featured items; (2) reveal their inherent characteristics and color; and (3) provide an appropriate, stimulating environment.

Some stores may have free-standing racks and open cases, where essentially uniform illuminance is suitable. Or important sales areas may be arranged so that luminaires could be selected or grouped to produce nonuniform illuminance. Still others may have showcases with glass tops and fronts, where certain types or positions of overhead luminaires might cause bothersome reflections that reduce the visibility of merchandise inside the case. Niches can have built-in linear or incandescent lighting, and track, surface, and recessed luminaires are widely employed for vertical displays.

Figure 26-26 illustrates a wall-lighting valance that has a spotlight in the end section, which is separately controlled for highlighting.

The shelf valance (Fig. 26-27) is useful for books, merchandise, and art objects, and for tasks not affected by veiling reflections. The room divider (Fig. 26-28) is applicable where unobtrusive divisions of space are desirable. Consult other references² for additional solutions.

Structural Lighting. Lighting systems that form a substantial part of the structure of a building, as distinguished from individual or groups of luminaires suspended from the ceiling or bracketed to walls, are examples of structural lighting.

A luminous ceiling of suspended plastic or other material is one such form (Fig. 26-29). Luminous ceilings are used less frequently today due to their relative inefficiency. One of the more common forms of structural lighting used today is an illuminated ceiling cove, where a recessed ceiling area is indirectly illuminated

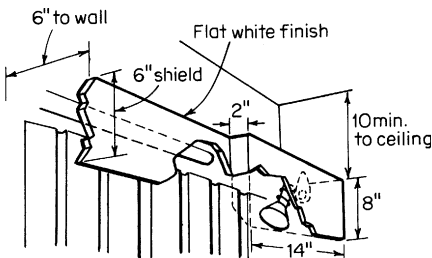


FIGURE 26-26 Valance and spotlight.

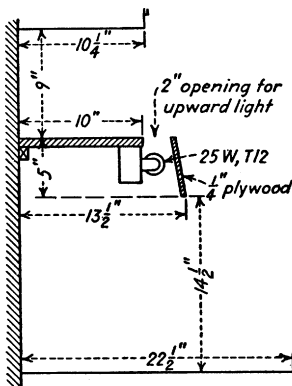


FIGURE 26-27 Shelf valance.

from a small shelf around the perimeter through the use of either bare lamp strips, or reflector luminaires designed to direct light out onto the ceiling. In most cove applications, the luminaires or lamps are hidden by the lip of the cove.

Codes and Standards. Local codes, national codes, international codes, federal standards, professional standards, and manufacturers' standards relate to specific requirements, which must be met in the construction and installation of a luminaire. Standards usually relate to minimum requirements (safety, construction, or performance), which may be exceeded to provide a better product.

Some codes and standards deal with fire and safety (electrical, mechanical, and thermal); others relate to performance (photometric) and construction (materials and finishes). They will vary to some extent depending on geographic location and end use of equipment. Conformance to the appropriate set of specifications is often determined by certified laboratory tests. Certification is often denoted by an identifying label. Local inspection agencies may or may not rely on conformance to national, federal, or industrial codes and standards.

Information regarding local codes may be obtained from electrical inspection departments. Several other code jurisdictions may apply to regional and state codes. The National Electrical Code (NEC) and similar codes in most major countries throughout the world state specific electrical requirements, which must be met by all electrical equipment, including luminaires. They have been developed by safety protection and inspection agencies in conjunction with fire-protection agencies.

The Underwriters' Laboratories, Inc. (UL) and similar groups in other countries publish minimum safety standards for electrical and associated products which are in conformance with the respective electrical codes of their country. They have testing laboratories to which equipment must be submitted for listing. Most manufacturers design luminaires to meet these standards.

The Life Safety Code³ (National Fire Protection Association 101) covers the requirements of exit signs and emergency lighting. Many models of standard and emergency exit signs are designed to meet NFPA-101 luminance standards, and retrofit kits permit easy conversion to more efficient sources. Signs equipped with battery packs must remain lighted a minimum of 90 min when their normal electric power fails. Engineers are encouraged to check for enactments of specific states regarding the required positions (such as requirements for not only the overdoor location, but also a low-level exit sign) and performance attributes (letter configurations, color, etc.) of exit signs.

Building codes also have requirements for egress lighting. The NFPA-101 *Life Safety Code* identifies occupancies that require emergency lighting. Most codes call for lighting the exit passageways

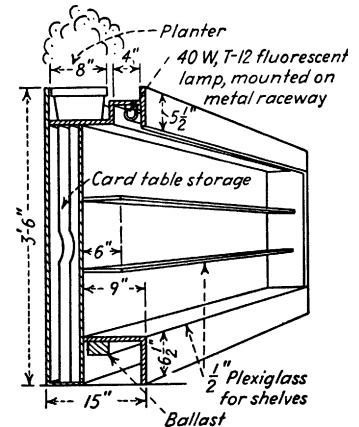


FIGURE 26-28 Room divider.

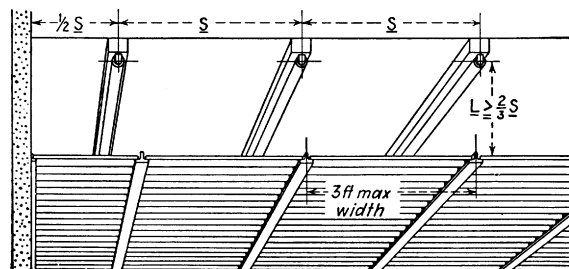


FIGURE 26-29 Luminous ceiling.

to a minimum illuminance of 1 fc on the floor for a period of $1\frac{1}{2}$ h after normal power fails. Luminaires containing fluorescent emergency ballasts having suitable, continuously charged battery packs can be positioned to meet requirements with acceptable uniformity. Ballasts providing instant restrike of high-pressure sodium luminaires are also available.

In addition to construction and safety standards, there are national and state energy-efficient lighting regulations which followed the federal Energy Policy Act of 1992. For commercial buildings, provisions of the latest ASHRAE/IESNA Standard 90.1, 2004 may prevail. Except for emergency lighting powered by battery, generator, or other alternate power source, which is automatically off during normal building operation, under this standard the lighting system must adhere to the following.

1. In buildings larger than 465 m² (5000 ft²), automatic lighting shutoff of building lighting is required in all spaces, except for lighting specifically designed for 24-h use. This may be accomplished on a scheduled shutoff basis or through occupant sensors.

An independent schedule must be provided for areas up to 2323 m² (25,000 ft²), but not more than one floor.

Spaces with ceiling-height partitions must have at least one control device to independently control the general lighting within the space, actuated manually by an occupant or automatically by sensing an occupant.

2. Luminaires for one or three fluorescent lamps greater than 30 W each must use two-lamp tandem-wired ballasts instead of single-lamp ballasts, when two or more luminaires are in the same space, and on the same control device. This does not apply to recessed luminaires more than 3 m (10 ft) apart measured center to center, individually mounted surface or pendant luminaires, luminaires with single-lamp electronic ballasts, luminaires with no available pair, or luminaires on emergency circuits.
3. Internally illuminating exit signs shall not exceed 5 W per face.

The 90.1 Standard includes important sections on installed interior lighting power and luminaire wattage. Power limits are computed by either the “building are” or the space-by-space method. Tables give maximum lighting power density (LPD) in watts per square foot for typical interior spaces. For example, enclosed offices are 1.1 W/ft², open-plan offices are 1.1 W/ft², classrooms/lecture/training spaces are 1.4 W/ft², and restrooms are 0.9 W/ft², and so on. The standard should be reviewed so that various exceptions can be considered. Other examples are for exterior lighting of a building entrance with canopy, 1.25 W/ft²; without canopy, 30 W/ft of door width; and 0.2 W/ft² for lighting vertical facade area, or 5 W/ft of illuminated wall or surface length.

Legislation requiring adherence to ASHRAE/IESNA 90.1 varies considerably among the states. Engineers are urged to check with appropriate agencies for latest information. Certain states mandate statewide conformance to state-developed energy codes for commercial buildings which meet or exceed ASHRAE/IES 90.1.

The desire of commercial, industrial, and institutional facility managers to reduce costs while maintaining and/or improving the visual environment for occupants also adds to the priority placed on energy conservation in lighting systems. Fortunately, major progress has been made in rating the combined efficacy of luminaires and the lamps and ballasts they contain. Also, modest-cost lighting control devices are available, which quickly pay for themselves by saving energy. See further information, see the subsection on energy conservation later in Sec. 26.9. There are also opportunities and benefits from integrating lighting with other building systems.

REFERENCES ON LUMINAIRES AND LIGHTING SYSTEMS

1. NEMA LE 4-2001, Recessed Luminaires; Ceiling Compatibility, National Electrical Manufacturers Association, www.nema.org
2. RP-2-015, *Lighting Merchandising Areas (A Store Lighting Guide)*, Illuminating Engineering Society of North America.

3. NFPA 101, *Life Safety Code*, 2006 ed., National Fire Protection Association.
4. ASHRAE/IESNA Standard 90.1/2004, *Energy Standard for Buildings Except Low-Rise Residential Building*, American Society of Heating, Refrigerating and Air-Conditioning Engineers & Illuminating Engineering Society of North America, 2004.

26.8 LUMINAIRE PHOTOMETRIC DATA

Types of Photometric Data. Luminaire manufacturers provide laboratory-measured and computed photometric and physical data required for lighting system analysis. The physical data include dimensions, finishes, light-control materials, number of lamps, types of lamps, etc. The photometric data include a luminous intensity (candela) distribution, zonal lumens, luminaire efficiency, coefficients of utilization, luminances, and for some systems, visual comfort probability (VCP) values.

Luminous Intensity (Candela) Distribution. A luminous intensity or candela distribution curve is a graphical presentation of the distribution of light about a lamp or luminaire. Such presentations contribute valuable information to guide the lighting designer in determining the suitability of lighting equipment for application in various fields. As a background for using distribution curves, it is first necessary to understand how they are obtained.

The candelas in any direction from a light source equals the illumination produced on a plane at right angles to the light rays times the square of the distance from the lamp to the point of measurement ($I = E \times D^2$). For accurate measurements the distance should be at least 5 times the largest dimension of the source.

To get sufficient data for a lamp or luminaire, readings are usually taken at a series of horizontal and vertical angles around a luminaire. Vertical angles may range from 0° (straight down) through 180° (straight up) with a spacing of 2.5° , 5° or 10° , while for most indoor luminaires, readings generally have a horizontal angle spacing of 22.5° . Horizontal symmetry and lack of uplight or downlight may limit the number of angles that are needed to fully describe a luminaire's intensity distribution. The luminous intensity values are typically plotted on a polar plot (Fig. 26-30) and may be shown for more than one horizontal angle when the distribution varies across the different axes. The line connecting a series of such points forms the intensity distribution curve. For concentrated light sources such as searchlights and spotlights, photometric readings are often required to be 1° or 2° apart.

The luminous intensity values reported for a particular manufacturer's luminaire apply to a particular lamp and its rated lumen output. If a lamp of identical physical size and light distribution, but having different rated lumens is applied in the luminaire, the luminous intensity values can simply be modified by the ratio of the rated lamp lumens for the new lamp

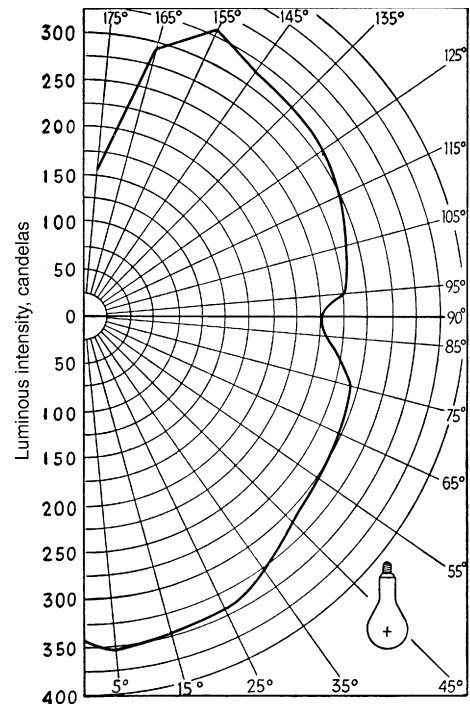


FIGURE 26-30 Distribution curve of a 3700-lm 200-W incandescent lamp. For convenience, the curves of axially symmetrical-type units show a single angle that is repeated at all other horizontal angle (0° or 360°). Luminous intensity in candelas is often referred to as a *candlepower distribution curve*.

versus the photometric test lamp. If the lamp is of different size or different distribution, then a new photometric report is needed to accurately quantify the luminaire's modified intensity distribution.

Zonal and Total Lumens. The total lumens of a light source are obtained by adding the lumens in the various angular zones. The zonal lumen values are readily computed by multiplying the average candelas around a lamp or luminaire at the center of a vertical angle zone by the zonal constant for that zone. For example, in Table 26-15, at 55°, which is the center of the 50° to 60° zone, the 300-cd reading from Fig. 26-37 is multiplied by 0.90, the zonal constant for this zone, giving 270 lm in that zone for the 200-W lamp. Zonal constants for the usual 18 test zones are simply numerical values of the solid angle subtended by that zone, which is the area in square feet within each zone on the surface of a sphere having a radius of 1 ft.

Luminaire Efficiency. The efficiency of a luminaire is expressed in terms of its lumen output divided by the rated lumens of the lamp or lamps. For example, if the 200-W lamp in Fig. 26-30 is placed in a white-glass enclosing globe whose candlepower distribution shows an output of 2960 lm, the efficiency of the luminaire is 2960 divided by 3700, or 80%.

Coefficients of Utilization. A coefficient of utilization (CU) is a number used in general lighting calculations and represents the ratio of the lumens received on the work plane from a uniform layout of luminaires to the lumens emitted by the luminaires' lamps alone. CUs are calculated using a uniform method and are tabulated for various room shapes and reflectances and are applied in the lumen method (discussed later).

Luminance and VCP. Average luminances calculated at various luminaire angles are part of direct-glare evaluations of VCP. Calculated VCP ratings of lighting installations using specific luminaire photometry, for various size rooms of given reflectances and illumination levels, may be reported. These ratings express the percentage of people who, if seated in the most undesirable location

TABLE 26-15 Tabulation of Candelas and Lumens in the Various Zones in the Curve of Fig. 26-37 (Computation of lumens from candelas)

Angle	Candelas	Zone	Zonal constant	Zonal lumens
0	347			
5	352	0–10	0.10	35
15	348	10–20	0.28	97
25	342	20–30	0.46	157
35	326	30–40	0.63	205
45	307	40–50	0.77	236
55	300	50–60	0.90	270
65	288	60–70	0.99	285
75	285	70–80	1.06	302
85	259	80–90	1.09	282
90	257			
95	271	90–100	1.09	295
105	278	100–110	1.06	295
115	290	110–120	0.99	287
125	307	120–130	0.90	276
135	308	130–140	0.77	237
145	313	140–150	0.63	197
155	329	150–160	0.46	151
165	280	160–170	0.28	78
175	153	170–180	0.10	15
Total lumens	...	...	...	3700

within the installation (4 ft from the center of the back wall and 4 ft above the floor), will be expected to find it acceptable. VCP was developed to quantify the glare of lensed fluorescent troffers, although it is often also applied to parabolic troffers. It cannot be applied to small downlights, HID luminaires, or luminaires with uplight, so its utility is somewhat limited. The CIE provides an alternate glare evaluation system, unified glare rating (UGR), that may apply to a wider range of luminaire types, but it is not widely used in the United States.

Luminaire Spacing Criteria (SC). The maximum permissible spacing for a luminaire is given in the Photometric Report provided by the manufacturer. These spacing limitations are related to the mounting height (usually above the work plane) and apply only to direct and semidirect luminaires. The maximum luminaire spacing center-to-center should not exceed the SC value times the mounting height (MH) and are often listed for the directions along and across the lamps for linear fluorescent luminaires. Observance of such limitations usually will ensure satisfactory uniformity of illumination throughout the major portion of the room so that all parts of the area will be equally suitable for the intended use. Peripheral areas may require special treatment, as indicated below. Illuminance is usually considered uniform if the maximum and minimum values are within plus or minus one-sixth of the average illuminance in the area. Closer spacing than indicated by the spacing criterion improves uniformity and reduces shadows. For luminaires with a large portion of light directed upward, computer software that performs point-by-point calculations can be applied to assess system uniformity.

The distance between luminaires and the wall should not exceed one-half the distance between luminaires. Where desks or benches might be located along the wall, the distance between luminaires and the wall should not exceed $2\frac{1}{2}$ ft. Likewise, the ends of continuous rows of fluorescent luminaires should preferably be within 6 to 12 in of the wall, unless this would provide a high luminance “scallop” on the adjacent wall. Additional luminaires or luminaires having a greater number of lamps may be required adjacent to the walls, particularly where walls have low reflectance. Where direct and semidirect luminaires are used under such conditions, the perimeter luminaires should be carefully located to avoid shadows on the task from the worker.

26.9 LIGHTING DESIGN

General Process. The lighting-design process can be broken down into four major parts: (1) determining the project goals, (2) collecting the space criteria and selecting the desired lighting system performance criteria, (3) making design decisions, and (4) evaluating the completed project. The design process may require changes in decisions (3) until the project goals have been satisfied.

Project Goals. These are the conceptual objectives of a whole project. The designer must have knowledge of the appearance requirements of the job, including the style of the architecture; whether a corporate image is to be projected; whether construction is for long life or of a speculative nature; whether young or old persons will be using the facility; and any other objectives of the project which will affect the lighting design.

Space Criteria. These are criteria which originate from outside the engineering discipline. They include identification of visual tasks and their locations and frequency, space dimensions, work-plane locations, reflectances, daylight apertures, space temperature and dirt conditions, voltage, operating schedules, cost budgets, power and energy budgets, and codes. These criteria should represent the best available information which can be obtained from the owner, architect, or designer.

Performance Criteria. These are criteria which originate from within the illuminating engineering discipline. They include illuminance levels for task performance and safety, visual comfort data, luminance ratios, other quality considerations. These criteria can be found in various American

TABLE 26-16 IESNA Illuminance Categories and their recommended values.

Illuminance category	Footcandles	Lux
Occasional tasks		
A	3	30
B	5	50
C	10	100
Common tasks		
D	30	300
E	50	500
F	100	1,000
Special tasks		
G	300–1,000	3,000–10,000

Note: The letter categories have the following descriptors:

- A Public spaces with dark surroundings
- B Simple orientation for short, temporary visits
- C Working spaces where visual tasks are only occasionally performed
- D Performance of visual tasks of high contrast or large size
- E Performance of visual tasks of medium contrast or small size
- F Performance of visual tasks of low contrast or very small size
- G Performance of visual tasks near threshold

National Standards Institute practices (Office,¹ School,² Industrial,³ Roadway⁴), in IES recommended practices and committee reports and in the IES Lighting Handbook.

Lighting design has long been known to involve more than selecting and positioning luminaires to provide recommended illuminances on visual tasks, wherever they are located in horizontal, inclined, or vertical work planes. The Committee on Quality of the Visual Environment of the Illuminating Engineering Society of North America, and that society's application committees, have developed matrices of quality issues for various types of interiors (Table 26-16 and Fig. 26-31). These matrices remind engineers and designers of specific aspects (source/task/eye geometry, color appearance, flicker, direct glare, etc.¹) which merit very important, important, somewhat important, or no consideration for the areas involved. For example, industrial spaces might have matrices with sections for basic tasks identified as raw-materials processing, materials handling, component manufacture, machining, assembly, warehouse and storage, inspection, service spaces, welding, and manual crafting. Some applications could be subdivided—for instance, the warehouse and storage section might have three rows of criteria ratings, indicating the priority of consideration for inactive, active and active (small items). The assembly section could have rows for simple, moderately difficult, difficult, very difficult, and exacting assembly. These matrices appear in the IES Lighting Handbook.

Design Decisions. All the above criteria along with the project goals need to be evaluated when making major design decisions. These major decisions include light-source selection, luminaire selection and mounting, maintenance-procedure determination, calculation-methods selection, luminaire-layout arrangement, and control planning (switching, dimming). Decisions involving tradeoffs and compromises are often necessary.

Evaluation. No design process is complete until one has evaluated the results to see that the project goals have been met. Computer software and hand calculation methods exist to provide detailed point-by-point work plane or room surface analysis grids or average work plane illuminance for evaluating lighting layouts during the design phase. Many of these programs are also able to provide

I. Interior locations and tasks		Very important ☐ Important ☐ Somewhat important ☐ Blank = Not important or not applicable																							
		Appearance of space and luminaires	Color appearance (and color contrast)	Daylighting integration and control	Direct glare	Flicker (and strobe)	Light distribution on surfaces	Light distribution on task plane (Uniformity)	Luminances of room surfaces	Modeling of faces or objects	Point(s) of interest	Reflected glare	Shadows	Source/task/eye geometry	Sparkle/desirable reflected highlights	Surface characteristics	System control and flexibility	Special considerations	Notes on special considerations	Illuminance (horizontal)	Category or value (lux)	Illuminance (vertical)	Category or value (lux)	Notes on Illuminance - see end of section	Reference chapter(s)
Design issues																									
Offices (13)																									Ch. 11
Filing (see reading)																									
General and private offices (see reading)																									
Open plan office																									
Intensive VDT use																		(14,15)					B		
Open plan office																									
Intermittent VDT use																		(14,15)					E		
Private office																									

FIGURE 26-31 The IESNA Handbook Design Guide categorizes important aspects of the visual environment and lists illuminance data for a wide variety of visual tasks. (Reprinted from the *IESNA Lighting Handbook*, 9th ed., with permission from the IESNA.)

informative computer renderings of the luminance patterns across a space. The lighting designer should also evaluate the interior. Battery-powered emergency incandescent-lamp units are widely employed to light aisles and corridors of industrial buildings, and equipping a predetermined portion of fluorescent luminaires with emergency ballasts can provide the prescribed illuminance levels for persons to leave their workstations and follow planned routes of egress. Such ballasts utilize high-temperature nickel-cadmium batteries, which results in fluorescent-lamp light output of sufficient duration to meet life safety code and UL standards (Table 26-17). Models are listed for both magnetic and electronic ballasts, for linear and compact fluorescent lamps, as combination units for both normal and emergency operation. In larger buildings, the emergency power source may be a generator that powers a number of different circuits within the building.

See Sec. 26.5 (paragraph on HID lamp operation) for standby illumination when HID lamps are extinguished by severe voltage dips or momentary power failures.

Veiling Reflections. Substantial losses in task contrast and hence in visibility and visual performance can result when light sources are reflected in such subtly specular (shiny) visual tasks as typing on bond paper. The apparent *veil* that is cast over a task when a light source is reflected in it may be so subtle as to be undetectable by the eye. Many factors contribute to veiling reflections and each of them, individually, has long been known. The problem is to integrate the effects of these interrelated factors. The factors are the visual task and its specularly; the worker's orientation, location, and viewing angles; and the lighting-system layout and luminaire light distribution and polarization.

The following are guidelines for reducing veiling reflections:

1. Where possible, written or printed tasks should be on matte paper using nongloss inks. The use of glossy paper stock and hard pencils should be minimized.
2. Light-source positions on either side and behind the workers are preferred.
3. Where work positions can be determined, substantial gains can be made by not positioning lighting equipment in the general area above and forward of the occupant's position for horizontal tasks, or at a position where veiling reflections would result for tasks of other orientations.
4. The use of luminaires with specific distributions and polarization characteristics for reducing reflections should be considered.
5. Side lighting such as from windows is effective in reducing veiling reflections. From the standpoint of visual comfort, workers should be positioned so their line of sight is parallel to or away from windows—rather than facing them.
6. Any decision on a lighting installation should also include considerations of its efficiency and the visual comfort in the space.

VDT (Computer) Criteria. One of the most common visual tasks that presents special lighting considerations is the visual display terminal (VDT). Although the front of the VDT is self-illuminated and the alphanumeric characters are visible without external lighting, there are typically other paper-background seeing tasks whose visibility are dependant on general or localized lighting systems. In

TABLE 26-17 Illuminance Levels for Safety*

Hazards requiring visual detection	Slight		High	
	Low	High	Low	High
Normal activity level [†]				
Illumination level				
Footcandles	0.5	1.0	2.0	5.0
Lux	5.4	11.0	22.0	54.0

*Minimum illumination for safety of personnel, absolute minimum at any time and at any location on any plane where safety is related to seeing conditions.

[†]Special conditions may require different levels of illumination.

addition, overall environmental luminance considerations call for general (ambient) illumination, which can be provided from a variety of luminaire distributions, all the way from totally direct to totally indirect.

A major specialized consideration involves the location and luminance distribution of luminaires in spaces containing VDTs, and the geometric relationship of the VDT screen to these luminaires and to windows. Luminance ratios should be no more than 3:1 between paper-based visual tasks and an adjacent VDT screen or dark surface, and the same 3 to 1 ratio applies between the VDT screen and an adjacent dark surface. For adjacent light surfaces, the corresponding luminance ratio is 1:3. For remote dark surfaces, the maximum ratio is 10:1, and for remote lighter surfaces, 1:10. To control direct glare, and to largely avoid bothersome reflections in the VDT screen, the average luminance of direct luminaires in the lengthwise, crosswise, and 45° vertical photometric planes at 55° from nadir should preferably not exceed 850 cd/m², 350 cd/m² at 65°, and 175 cd/m² at 75° or more from nadir. The average luminance should never exceed 850, 350, and 175 cd/m² at 65°, 75°, and 85°, respectively. Movable task lighting should not exceed 50 fc on the horizontal work plane (see IESNA publication RP-1-04, American National Standard Practice for Office Lighting).

Indirect systems should not exceed 850 cd/m² of ceiling luminance at any angle, or more than 8:1 (preferably 4:1) in uniformity. Luminaires with both upward and downward light components should have luminances of 850 cd/m² or less at angles between 55° and 90° in the crosswise, lengthwise, and 45° vertical photometric planes.

Visual Comfort. Visual comfort may occur when there are no overly high luminances within a worker's visual field. High luminances can also distract and even reduce visibility. Luminaires and fenestrations which have luminances that are too high for the environment in which they are located will produce discomfort. Discomfort from direct glare is reduced by

1. Decreasing the luminance of lighting equipment or other sources of objectionable glare, such as windows and overhead skylights.
2. Diminishing the area of uncomfortable luminances (with glare zone luminance constant).
3. Increasing the angle between the source and line of sight.
4. Increasing the general luminance in the room.

A rating system based on the degree of freedom from discomfort glare in a proposed lighting installation is called visual comfort probability (VCP). This system is limited to use with direct-lighting fluorescent troffers and cannot be applied to HID luminaires, CFL downlights, and many other direct distribution luminaires. Evaluation is based on the following factors which influence subjective judgments of visual comfort: room size and shape; room-surface reflectances; illumination levels; luminaire type, size, luminance, maximum luminance, and light distribution; number of luminaires; luminance of the field of view; observer location and line of sight; and differences in individual glare sensitivity. Since each of these factors can vary considerably, a standard set of conditions has been established and used as a basis for VCP tables.

Direct discomfort glare should not be considered a problem in lighting installations if all three of the following conditions are satisfied:

1. The VCP is 70 or more.
2. The ratio of maximum to average luminaire luminance does not exceed 5:1 (preferably 3:1) at 45°, 55°, 65°, 75°, and 85° from nadir, crosswise and lengthwise.
3. Maximum luminaire luminances, crosswise and lengthwise, do not exceed the following values:

Angle above nadir, deg	Maximum luminance, (cd/m ²)
45	7710
55	5500
65	3860
75	2570
85	1695

Luminance Distribution. The luminance relationship of the various surfaces in the visual field is important. When the eyes scan a task, an adaptation level is established consisting primarily of the task luminance. As the eyes leave the task and look at an area of a different luminance, there is a sudden loss of sensitivity to see the contrast of the detail in the new area until the eyes can readapt after a short length of time. In order to see the detail of a visual task accurately and quickly, luminance ratios of appreciable areas in the visual environment should be kept low. Table 26-18 is an example of recommended luminance ratios for offices (ANSI/IES RP-1-04, American National *Standard Practice for Office Lighting*). To help achieve these ratios, room surface should be of high reflectance, as recommended for specific applications.

Energy Conservation. In any lighting design it is important to consider the following recommendations for the reduction of energy used for lighting. They are appropriate for designing new construction, in renovation work, and in operating and maintaining existing installations.

1. *Design Lighting for Expected Activity (Appropriate Illuminance for Seeing Tasks, with Less Light in Surrounding Nonwork Areas).* In some interiors (general offices, classrooms, certain production spaces, etc.) where work stations are in close proximity to each other, the task areas represent a high percentage of the total work plane (length times width), and therefore reasonably uniform task-level illuminance is appropriate throughout the space. In other cases, private offices, for example, the visual tasks may be critical and prolonged for only 20 to 30% of the work plane (such as the tops of the desk and credenza of the single occupant). The lighting designer, thus, has the opportunity to conserve energy by reducing illuminance in the nonwork portions of the room. Such energy savings are in addition to those received by lowered illuminance levels in hallways, other circulation areas, storage spaces, etc.

Open-plan offices often have movable furniture containing linear fluorescent task lighting, and low partitions which subdivide the space to give worker privacy. Luminaires mounted under overhead cabinets or shelves should be positioned if possible to avoid veiling reflections, and a convenient "on-off" switch should be provided. Such supplementary luminaires should be selected to provide illuminances throughout the task area which adequately augment levels of the general lighting system, since the contribution from the general lighting system may be reduced by the height of the shelves, cabinets, partitions, etc.

2. *Design with More Effective Luminaires and Fenestration.* The goal of both daylight and artificial illumination systems is to produce visual environments which result in rapid and accurate seeing. The goal is achieved in an energy-conserving manner by selecting luminance distributions and luminaire positions which enhance task visibility. For example, desks, drafting tables, and many other types of workstations involve paper-background tasks which use pencil, ink, typed, photocopied, or printed characters which have a specular component of reflection. Such tasks are best lighted from the side. With some acoustical ceiling-suspension systems, recessed fluorescent luminaires can be easily moved as work stations change, especially if the luminaires are powered by plug-in "flexible" wiring cables and connectors (Fig. 26-32). Luminaires for three or four fluorescent lamps can be wired to two wall switches for manual selection of 50 or 100% illuminance if two two-lamp ballasts are involved, and for 33, 67 or 100% if one single-lamp and one two-lamp ballast operate a three-lamp luminaire. Such switching arrangements conveniently permit reduced illuminance

TABLE 26-18 Recommended Luminance Ratios for Offices*

To achieve a comfortable balance in the office and limit the effects of transient adaptations and disability glare, it is desirable and practical to limit luminance ratios between areas of appreciable size from normal viewpoints as follows:

1- $\sqrt{3}$	between task and adjacent light surroundings
1- $\sqrt{3}$	between task and adjacent dark surroundings
1- $\sqrt{5}$	between task and more remote darker surfaces
1- $\sqrt{10}$	between task and more remote lighter surfaces

*These ratios, 3:1 or 10:1 are recommended as maximums; reductions are generally beneficial.

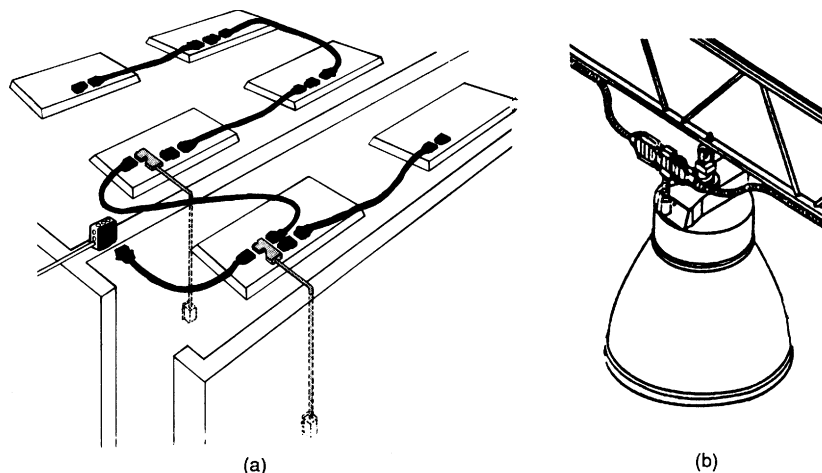


FIGURE 26-32 Flexible (plug-in) wiring systems for (a) commercial/institutional recessed and (b) industrial HID luminaires.

when it is adequate to supplement daylight in spaces with windows, and for the less demanding visual tasks during cleaning operations.

Daylight in areas which include exterior windows can be applied to save electric energy consumed by the electric lighting system. Because the quantity and quality of daylight varies greatly, windows require adjustable shades and blinds to control direct glare. Desks and other work stations should be oriented to minimize body shadows and to minimize veiling reflections (see IESNA publications RP-5, *Daylighting*).

Analysis of owning and operating charges can anticipate the present worth of future expenditures in a method known as "life cycle costing." Periods of 10 to 20 years are usually chosen as the "life" of a typical illumination system. The known or estimated time that future costs are expected to occur are converted to net present values. Such evaluations best show the economic benefits of more efficient, energy-conserving lighting systems.

3. *Use Efficient Light Sources (Higher Lumen per Watt Output).* Increased lamp efficacy obviously saves energy. Incandescent lamps have lower lumens per watt than any other family of general-service lamps. Also important are the annual hours that lighting is needed in a given space.* Table 26-12 lists many other characteristics that must be considered in selecting lamps. Some lumen per watt (lpw) guidelines:

Incandescent:

For equal life, lpw increases with wattage.

For comparable incandescent lamp options, increased life generally means lower lpw.

Krypton gas fill lamps give energy savings over lamp life.[†]

Tungsten-halogen capsules can give more lpw, or longer life, or both.

Undervoltage operation lowers lpw and increases life.[‡]

*Because of its small size and instant starting, and especially because of the low burning hours per year, incandescent lamps are the standard for broom closets even though their efficacy is low.

[†]Krypton-filled 34-, 52-, 67-, 90-, and 135-W longer-life lamps have lower efficacy than do 40-, 60-, 75-, 100-, and 150-W lamps.

[‡]For example, a 130-V 1000-h, 150-W argon-filled incandescent lamp operated at 120 V would have average life of approximately 1950 h, and produce initially approximately 2140 lm instead of its 2800-lm-rating if operated at 130 V.

Fluorescent:

32-W T-8 lamps are an obvious choice for 4-ft luminaires—greatly superior to 34-W cool white T-12 lamps in lumens per watt and CRI.

For given tube diameter and lamp current, long lamps have higher lpw than short lamps.

Longer burning hours per start increase lamp life.[§]

High CRI lamps using rare-earth phosphors have improved lpw as well as color rendition.

Compact fluorescent lamps can replace incandescent lamps in downlights, supplementary and adjustable task lights, and residential floor and table lamps.

System efficacy ratings should combine lamp, ballast, and luminaire performance.

High-intensity discharge:

If color is no factor, high-pressure sodium has highest lpw, long life, and good lumen maintenance. Metal halide provides good lpw and color. Since light output can decrease if operated in positions other than designated by the lamp manufacturer, a “tilt factor” is appropriate in design computations.

Standard Metal Halide lamps, in general, have noticeable problems with color consistency. Lamps shift to different shades of white and may not emit a uniform color of white light across all lamps in a system. Ceramic metal halide lamps and specially shaped arc-tube lamps help limit the color shift that occurs.

White high-pressure sodium lamps with 70 plus CRI ratings at 2800 K can be used with incandescent lamps (check for available wattages). 3200-K metal-halide lamps can be considered for retail and other commercial applications where warmer light-source color is desired.

4. Use More Efficient Luminaires. If a lighting system can deliver lumens to the work plane more efficiently, the wattage needed to achieve desired illuminance levels should be reduced, provided the luminaire intensity distribution is appropriate for the application being considered. Luminaire efficacy rating (LER) expresses, to the nearest whole number, the rated lumens per watt of a specific luminaire, equipped with specific lamps and ballasts.

The determination of LER considers luminaire efficiency to the nearest two-place decimal (three-place decimals may be used if desired), ballast factors rounded to the nearest two-place decimal, and input watts rounded to the nearest whole number. NEMA LE 5-2001 provides details on the calculation of LER⁶, calling for photometry in accordance with IESNA LM-41, and defines the procedure for calculating ballast factor. Preceding the LER number in manufacturers' literature are two letters, indicating the luminaire category: FL = fluorescent recessed lensed, FP = fluorescent recessed parabolic, FW = fluorescent wraparounds, FS = fluorescent strip, and FI =

A similar NEMA Standard LE 5B-1998 for open (HO) and closed-bottom (HC) HID industrial luminaires⁷, considered to have ballast factors of 1.0, gives minimum LERs for these luminaire types. Exempted are luminaires for HID lamps less than 150 W, special-application luminaires such as for hazardous areas, and luminaires using automatically switched quartz-lamp standby circuits.

Since rated ballast(s) input wattage is generated independently of photometric testing, existing photometric tests in compliance with IESNA LM-46 can be used to compute LER values. Because a variety of ballasts can be used with many luminaire designs, the specific ballast type must be reported in conjunction with the LER. See LE5B for further information.

1 Use Thermally Controlled Luminaires. Figure 26-12 shows that the ambient temperature near the luminaire, and the extent to which the heat produced by lamps and ballasts is retained, will have considerable effect on the light output. Tests show that maximum lamp efficacy occurs when the

[§]However, cathode improvements have greatly reduced the life penalty of shorter operating cycles. Combinations of lamp and energy cost may recommend turning off fluorescent lighting even for intervals as short as 10 min or less when the illumination is not needed.

lamp cold-spot temperature is approximately 104F.⁸ A four-lamp 40-W troffer 2 ft wide and 4 ft long with a prismatic enclosure can have temperatures up to 120 to 130F inside the lamp compartment, which can account for approximately a 15% reduction in light output. By passing room air through the lamp compartment (called “heat transfer” or “heat exhaust”), a thermal condition more favorable to light production can be achieved, and less of the lighting heat enters the occupied space.

2 Use Lighter Finishes on Ceilings, Walls, Floors, and Furniture. IES recommended practices for various types of interiors list desirable reflectances for room surfaces and furniture. For commercial and institutional interiors these would be 80 to 90% for ceilings, 50 to 70% for walls, 40 to 70% for partitions, 25 to 45% for furniture, 25 to 45% for office machines and equipment, and 20 to 40% for floors. Similar values are suggested for industrial spaces (except not less than 20% for floors), realizing that they are much more difficult to control, and pointing out that some color can be stimulating. Because lower CRI lamps are widely used in factory areas, the colors should be selected while illuminated by the type of lamps under which they will be seen.

Turn Off Lights When Not Needed. Because time is a factor in the formula for electrical energy, programs to conserve energy should minimize the operation of lighting systems when spaces are unoccupied, even for a modest period appropriate for the *traffic* pattern. This is an owner benefit and energy-saving procedure, in addition to varying illuminances to supplement daylight, and to fit tasks that have higher or lower visual demands.

Building codes/standards such as ASHRAE/IESNA 90.1 mandate switches in each space and auto-shutoff. Clock switches can turn luminaires on and off, and can activate either or both of two circuits wired to three- and four-lamp luminaires, as previously mentioned. A central processing unit could provide the capability for preset, digital, and automated control, plus override arrangements when lighting is needed during normal off periods.

Occupancy sensors can also control lighting systems, with adjustable time intervals after infrared or ultrasonic beams sense the presence or absence of people in the space covered. Some take the place of wall light switches for use in private offices and other small spaces. Specifiers should compare features available from different manufacturers.

In warehouses, shipping docks, and many outdoor lighted areas there are numerous times when illuminances can be reduced to save energy if “full output” is provided almost instantly and automatically when needed. High-low components using occupancy detectors of the passive infrared or ultrasonic type can be positioned to sense motion in areas leading to warehouse aisles, for example, which could be operating as low as 30% of normal wattage. A coded signal would be transmitted without control wires to receivers located in metal halide or high-pressure sodium luminaires, resulting in near instant normal light level. A short interval after the motion ends, the luminaires would switch back automatically to the low illuminance level. The infrared occupancy detector/transmitters are smaller and work best outdoors and in low-temperature locations. Ultrasonic models have better sensitivity, can respond to the slightest motion, and are particularly effective over narrow warehouse aisles. General-purpose transmitters permit switches, relays, photocells, or time clocks to operate the high-low system.

8. Keep Lighting Equipment Clean and in Good Working Condition. Early in the design stage, lighting equipment should be selected that will be easy to maintain: to change lamps, to periodically clean reflecting and light-transmitting components, and to easily reach ballasts and other electrical auxiliaries. It is also important to mount luminaires so that maintenance personnel can have access for servicing, or provide means for lowering equipment to more convenient levels. The continuing effectiveness of lighting systems depends on good maintenance. In existing facilities, systematic reevaluations may reveal maintenance procedures which reduce the consumption of lighting energy.

Programs should include considerations of (1) group replacement of lamps at 70% to 80% of expected average lamp life and (2) scheduled luminaire cleanings that help the owner receive the light which the system was designed to provide. Both justify higher light loss factors to reduce the number of luminaires needed. Lighting maintenance companies in metropolitan areas can be engaged to perform relamping, cleaning, and repair functions, and to provide proper cleaning compounds, ladders, scaffolds, etc. In-house maintenance departments should develop and post instructions

which cover procedures and frequency of different services, coordinated to minimize disruption of essential activities.

Lighting and the Thermal Environment. Effective building design requires a provision for efficient utilization of dissipation of lighting heat. The benefits of integrating building heat in lighting design are: (1) improved performance of the air-conditioning system, (2) more efficient handling of lighting heat, and (3) more efficient lamp performance if fluorescent lamps are the light source.

The control and removal of lighting heat before it enters the occupied space can reduce heat in that space, reduce air changes and fan horsepower, lower temperature differentials required in the space, enable a more economical cooling-coil selection because of the higher temperature differential across the coil, and reduce luminaire and ceiling temperature, thereby minimizing radiant effects.

The degree to which any of these benefits may be obtained depends on many variables such as the quantity of energy involved, the type of heat-transfer mechanism, the temperature difference between source and sink, and the velocity and quantity of air available for heat transfer.

REFERENCES ON LIGHTING DESIGN

1. RP-1-04, *American National Standard Practice for Office Lighting*, Illuminating Engineering Society of North America, www.iesna.org
2. RP-3-00, *Lighting for Educational Facilities*, Illuminating Engineering Society of North America, www.iesna.org
3. RP-7-01, *Lighting Industrial Facilities*, Illuminating Engineering Society of North America, www.iesna.org
4. RP-8-00, *Roadway Lighting*, Illuminating Engineering Society of North America, www.iesna.org
5. *IES Lighting Handbook*, 2000.
6. LE 5-2001, *Procedure for Determining Luminaire Efficacy Ratings for Fluorescent Luminaires*, National Electrical Manufacturers Association (NEMA), www.nema.org
7. LE 5B-1998, *Procedure for Determining Luminaire Efficacy Ratings for High-Intensity Discharge Industrial Luminaires*, National Electrical Manufacturers Association (NEMA), www.nema.org
8. Treado, S.J., *Lighting and HVAC, Lighting Design and Application*, July 1991, p. 18.

26.10 QUANTITY AND QUALITY OF ILLUMINATION

Lighting is provided so that people can perform visual tasks. Visual performance is a function of a number of fundamentally important factors. Some of these are the size of the object or detail to be seen, the contrast of the detail with its immediate background, the luminance of the object, the time available to see it, the luminance relation between the object and its surroundings, the visual capability of the human seeing machine, and the level of personal motivation.

The difficulty of the visual task is determined by the size and contrast of the task details. Other factors being equal, small tasks require more illuminance for a given level of visual performance than larger tasks. Similarly, low contrast between the task details and their background justifies higher illuminance levels. The IESNA procedure for selecting illuminance⁵ employs seven generic types of interior activity, identified by the first seven letters of the alphabet, as described in Table 26-19, Letter categories A, B, and C, called for modest levels of general lighting throughout the spaces. Categories D, E, and F required minimum illuminances on the task, and G involves higher illuminances on more difficult tasks, obtained by a combination of general and local (supplementary) lighting.

In the past, modifications to these recommended illuminance levels were made based on characteristics of the space, task and age of the occupants. In the current method, the IESNA provides less guidance on when to increase or decrease the recommended values, but suggests that 1/3 increase or decrease to these values be applied if actual conditions or the occupant's age justifies such a change.

TABLE 26-19 Typical Recommended Illuminances

Area or activity	Illuminance category	Recommended illuminance, fc*
Industrial assembly or inspection		
Simple	D	30
Moderately difficult	E	50
Difficult	F	100
Exacting	G	300‡
Machine shops		
Rough bench or machine work	D	30
Medium bench or machine work, ordinary automatic machines, rough grinding, medium buffing and polishing	E	50
Fine bench or machine work, fine automatic machines, medium grinding, fine buffing and polishing	G	300
Extrafine bench or machine work, grinding, fine work	G	300‡
Materials handling		
Wrapping, packing, labeling	D	30
Picking stock, classifying	D	30‡
Loading, inside truck bodies and freight cars	C	10
Reading copied tasks		
Thermal copy, poor copy	F	75§
Xerograph	D	30
Xerography, third generation and greater	E	50
Reading handwritten tasks		
#3 pencil and softer leads	E	50§
#4 pencil and harder leads	F	75§
Ball-point pen	D	30§
Felt-tip pen	D	30
Handwritten carbon copies	E	50
Whitelboards	D	30
Chalkboards	E	50§
Reading printed tasks		
6-point type	E	50§
8- and 10-point type	D	30§
Glossy magazines	D	30§
Maps	E	50
Newsprint	D	30
Typed originals	D	30
Typed second carbon and later	E	50
Telephone books	E	50

*See 9th or later edition of *IES Lighting Handbook* for complete listing. Multiply footcandle values listed above by 10 for corresponding rounded-off lux values (1 footcandle = 10.76 lux).

†Use information in Table 26-26 to determine whether "normal" or "difficult" task column is appropriate.

‡Obtained by a combination of general and supplementary lighting.

§Subject to veiling reflections. Glossy surfaces are especially subject to veiling reflections, and it may be necessary to shield the task, reorient it, or select a lighting system that avoids veiling reflections.

26.11 CALCULATING MAINTAINED ILLUMINANCE

Maintained illuminance is the illuminance that will be provided by a lighting system at some future point in time, and generally considers a variety of light-loss factors. Lighting systems are generally designed so that the maintained illuminance prior to cleaning, relamping, etc. is near the target illuminance level. A new and clean lighting system, therefore, will typically provide work plane illuminance levels above the target level to account for the losses that occur over time.

Light-Loss Factor. In calculating maintained illuminance (the lowest level before maintenance procedures are instituted) a light-loss factor (LLF) is used to take into account losses in light output due to temperature and voltage variations, ballast factors, lamp position (tilt) factors, equipment operating factors, thermal factors, dirt accumulation on luminaire and room surfaces, lamp depreciation, maintenance procedures, and atmospheric conditions. The effect of these light losses can be seen in the example shown in Fig. 26-33. It is important that all causes of light loss be investigated and maintenance procedures be established in the lighting-design stage to assure adequate illumination is provided in an economical manner without wasting energy.

LLF Determination. The LLF (formerly called maintenance factor) is mainly the product of the ballast factor (BF), lamp lumen depreciation factor (LLD), the luminaire dirt depreciation factor (LDD), the room-surface dirt depreciation factor (RSDD), and lamp burnout factor (LBO). Other factors such as ambient temperature factor (for fluorescent) and voltage-to-luminaire factor (for incandescent) may also be applied. Data on LLD are available from lamp manufacturers. LBO is the

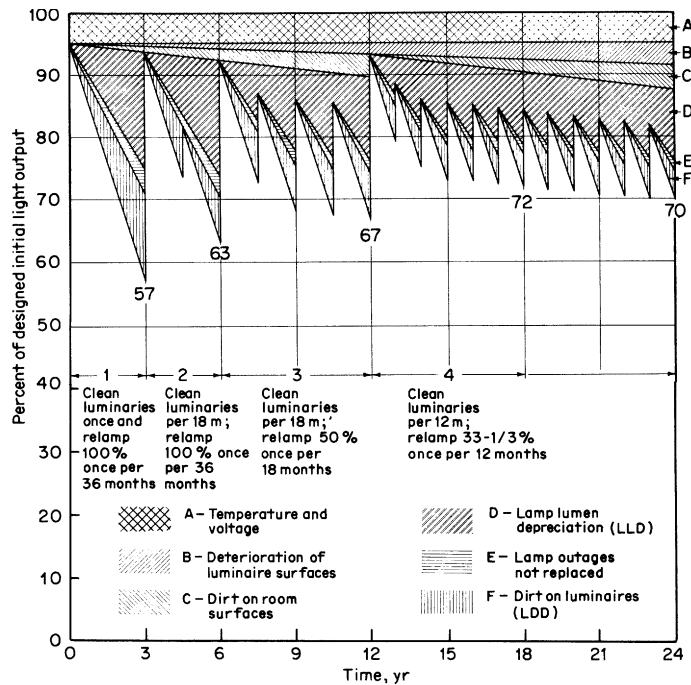


FIGURE 26-33 Effect of light loss on illumination level. Example shown is for enclosed surface-mounted luminaires with 40-W fluorescent lamps, operated 10 h a day, 5 days per week, 2600 h per year. Four maintenance systems are shown for comparison purposes.

ratio of lamps remaining lighted to the total in the original installation, if burnouts are not replaced immediately. LDD is obtained from curves, such as shown in Fig. 26-34, a knowledge of the amount of dirt in the room atmosphere, a knowledge of the length of time between luminaire cleanings, and the luminaire maintenance category, a Roman numeral from I to VI, which is based on the luminaire type (see Table 26-20). RSDD is obtained from a curve and table as shown in Fig. 26-35, where room size, luminaire distribution, room atmosphere, and cleaning cycle are known.

Example of calculation procedure. Given a direct type of luminaire of category IV, with 32-W fluorescent lamps (LLD = 0.92. Room atmosphere is very clean and cleaning is performed every 18 months. Room-cavity ratio is 2. Lamps are replaced at burnout.

BF = 0.94 (from ballast or luminaire manufacturer)

LLD = 0.92 (mean lumens/initial lumens from manufacturer's lamp tables)

LDD from Fig. 26-34 = 0.91

RSDD from Fig. 26-35 = 0.98

LBO = 1

LLF = $0.94 \times 0.92 \times 0.91 \times 0.98 \times 1.0 = 0.77$

26.12 CALCULATION OF AVERAGE ILLUMINANCE

General Lighting. The design of general lighting systems is governed by room dimensions, structural features, reflectances of room surfaces, mounting height of the luminaires, and the distribution and maintenance characteristics of the luminaire. The choice of the luminaire depends on the service to which it is to be put, which assumes a certain experience in selection, or other aids such as manufacturers' data, which assist the designer in making a selection appropriate from the standpoint of freedom from glare, efficiency, decorative value, and economy. The ultimate "luminance pattern" of the room is an important factor in the design.

The beginning concept of general lighting design is that of delivering a specified average illuminance level to a horizontal plane in a room. The light generated by the lamps in such a system is variously affected and considerably reduced by reflection, diffusion, and absorption as it impinges on reflectors and transmitting media in the luminaires and on ceilings, wall, floors, and on the objects in the room.

The Lumen (Zonal-Cavity) Method.¹ The lumen method is used in calculating the illuminance that represents the average of all points on the work plane in an interior. It is based on the definition of illuminance as luminous flux per unit area, or

where luminous flux is expressed in lumens. If the area is in square feet, the illuminance is in footcandles (lumens per square foot); if the area is in square meters, the illuminance is in lux (lumens per square meter).

Because not all the lamp lumens will reach the work plane owing to losses in the luminaire and at the room surfaces, they must be multiplied by a coefficient of utilization which represents the portion that reaches the work plane.

Since, the design objective is usually to maintain a minimum value of illuminance, factors must be applied to account for the estimated depreciation in lamp lumens, the estimated losses from dirt collection on the luminaire surfaces (including lamps), etc., that occur over time, or due to system components.

The zonal-cavity method considers the actual room as being made up of a ceiling cavity above the luminaires, a floor cavity beneath the work plane, and a room cavity located between the two (see Fig. 26-36).

In the general case, all these cavities are present. In the case of recessed or surface-mounted luminaires, the ceiling cavity is simply the ceiling. When the illuminance on the floor is to be determined, the floor cavity becomes the floor.

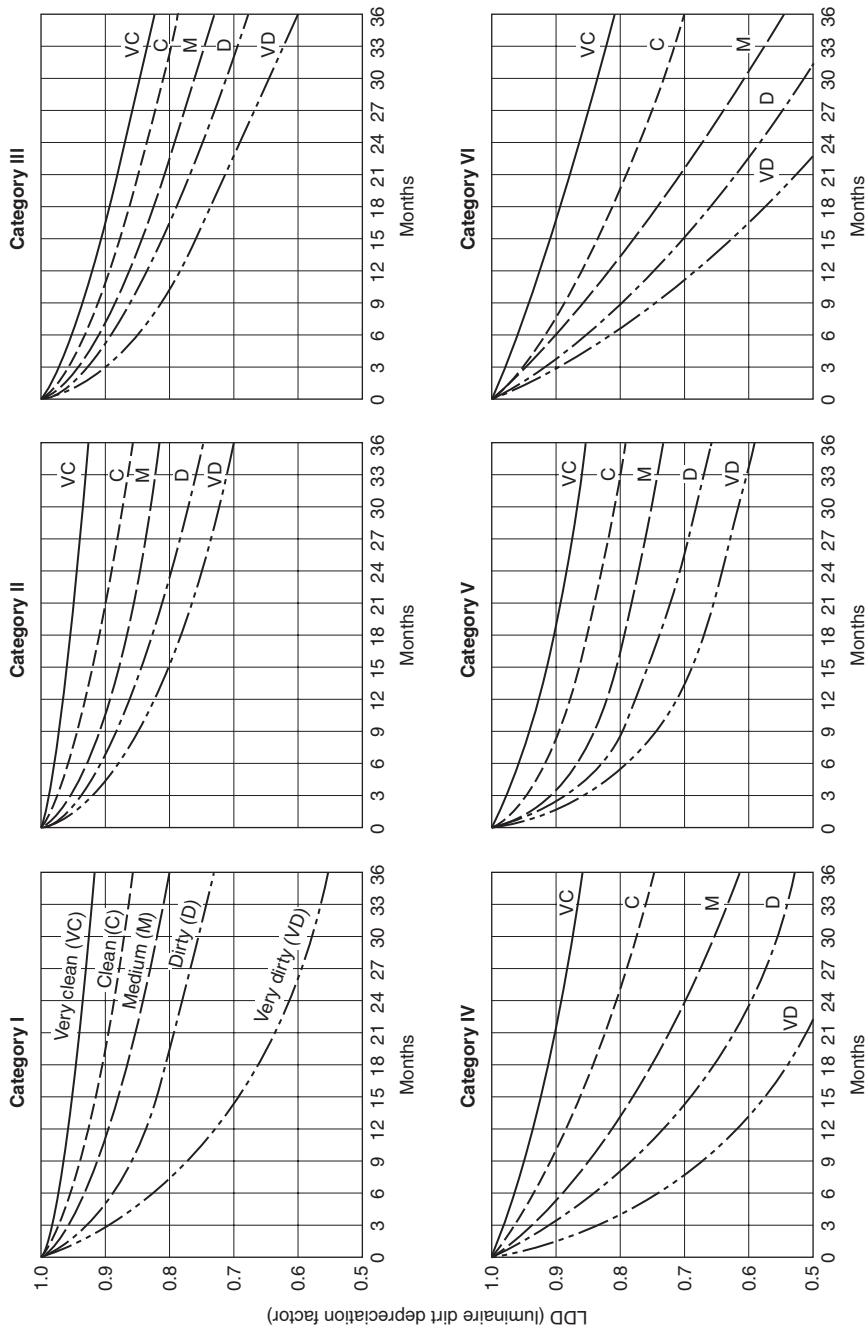


FIGURE 26-34 Luminance dirt depreciation (LDD) factors for the six luminance categories and for 5 levels of atmosphere dirtiness. (Reprinted from the *IESNA Lighting Handbook, 9th ed.*, with permission from the *IESNA*.)

TABLE 26-20 A General interpretation of the IESNA Luminaire Maintenance Categories for Luminaires

Maintenance category	Types of luminaires included in this category
I	Bare lamps, bare lamp strips, and globes
II	Open pendant luminaires with >15% uplight through top openings
III	Open pendant luminaires with <15% uplight through top openings
IV	Luminaires with an open bottom and closed top, such as a parabolic troffer or open downlight
V	Luminaires that are completely enclosed, typically with lenses
VI	Uplights with an open top and solid bottom

It is now possible to calculate numerical relationships called *cavity ratios*, which may be used to determine effective reflectance of the floor and ceiling and then to find the coefficient of utilization. The basic steps in the calculation of any average illuminance are as follows:

1. Determine cavity ratios for three cavities shown in Fig. 26-36 as follows:

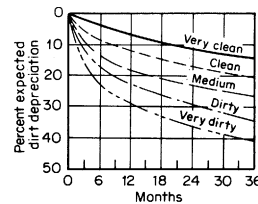
$$\text{Room-cavity ratio, RCR} = 5 \times h_{RC} (L + W) / (L \times W)$$

$$\text{Ceiling-cavity ratio, CCR} = 5 \times h_{CC} (L + W) / (L \times W) = \text{RCR } h_{CC} / h_{RC}$$

$$\text{Floor-cavity ratio, FCR} = 5 \times h_{FC} (L + W) / (L \times W) = \text{RCR } h_{FC} / h_{RC}$$

Where h_{RC} = height of room between luminaire plane and work plane; h_{CC} = distance from luminaire plane to ceiling; h_{FC} = height of work plane above floor; L = room length; and W = room width.

2. Obtain the *effective floor-cavity reflectance* (pfc) for the combination of floor and wall reflectances to be employed from Table 26-22.



Percent expected dirt depreciation	Luminaire distribution type																			
	Direct				Semidirect				Direct-indirect				Semi-indirect				Indirect			
	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40	10	20	30	40
Room-cavity ratio																				
1	.98	.96	.94	.92	.97	.92	.89	.84	.94	.87	.80	.76	.94	.87	.80	.73	.90	.80	.70	.60
2	.98	.96	.94	.92	.96	.92	.88	.83	.94	.87	.80	.75	.94	.87	.79	.72	.90	.80	.69	.59
3	.98	.95	.93	.90	.96	.91	.87	.82	.94	.86	.79	.74	.94	.86	.78	.71	.90	.79	.68	.58
4	.97	.95	.92	.90	.95	.90	.85	.80	.94	.86	.79	.73	.94	.86	.78	.70	.89	.78	.67	.56
5	.97	.94	.91	.89	.94	.90	.84	.79	.93	.86	.79	.72	.93	.86	.77	.69	.89	.78	.66	.55
6	.97	.94	.91	.88	.94	.89	.83	.78	.93	.85	.78	.71	.93	.85	.76	.68	.89	.77	.66	.54
7	.97	.94	.90	.87	.93	.88	.82	.77	.93	.84	.77	.70	.93	.84	.76	.68	.89	.76	.65	.53
8	.96	.93	.89	.86	.93	.87	.81	.75	.93	.84	.76	.69	.93	.84	.76	.68	.88	.76	.64	.52
9	.96	.92	.88	.85	.93	.87	.80	.74	.93	.84	.76	.68	.93	.84	.75	.67	.88	.75	.63	.51
10	.90	.92	.87	.83	.93	.86	.79	.72	.93	.84	.75	.67	.92	.83	.75	.67	.88	.75	.62	.50

FIGURE 26-35 Room-surface dirt depreciation (RSDD) factors, based on space dirt level, room surface cleaning interval, and CIE luminaire distribution type.

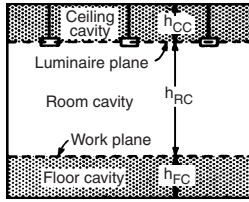


FIGURE 26-36 Room cavities.

3. Obtain the *effective ceiling-cavity reflectance* (p_{cc}) for the combination of ceiling and wall reflectance to be employed from Table 26-23. Note that, for surface-mounted or recessed luminaires, $CCR = 0$ and the ceiling reflectance may be used as the effective cavity reflectance.

4. Obtain the coefficient of utilization for the luminaire for a 20% effective floor-cavity-reflectance condition (tables like 26-21), interpolating between tabulated values as required to match room size and ceiling- and wall-reflectance combinations.

5. If the *effective floor-cavity reflectance* (p_{fc}) obtained in step 3 differs significantly from 20%, obtain a multiplier from Table 26-23 or Table 26-24. Multiply the coefficient of utilization by this multiplier.

6. Determine average maintained illuminance by the following formula:

$$E_{ave} = \frac{(\text{rated lamp lumens / luminaire}) \times CU \times LLF^*}{\text{area / luminaire}}$$

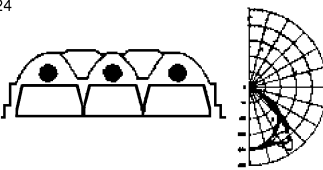
If initial illuminance is desired, use a LLF factor that considers only the LLF components that will occur when the system is new, such as the ballast factor. When the desired average maintained illumination is known, the formula can more conveniently be expressed as

$$\text{Number of luminaires required} = \frac{E_{desired} \times (\text{room area})}{(\text{rated lamp lumens / luminaire}) \times CU \times LLF^*}$$

$$\text{Area / luminaire} = \frac{(\text{rated lamp lumens / luminaire}) \times CU \times LLF^*}{E_{desired}}$$

This area per luminaire when divided by the luminaire length gives the approximate spacing between continuous rows, or it may be divided into the total room area to determine the number of

TABLE 26-21 Coefficients of Utilization of a Troffer Designed for Spaces with VDTs

Typical intensity distribution Typical luminaire 24  2 x 4.3-Lamp parabolic troffer with 3" semi-spac. louvers, 18 cells		$p_{cc} \rightarrow$	80			70			50			30			10			0
		$p_{w} \rightarrow$	70	50	30	70	50	30	50	30	10	50	30	10	50	30	10	0
		RCR		EFF = 72.7%			% DN = 100			% UP = 0			Lamp = (3) F32T8 SC (along, across, 45°) = 1.3, 1.6, 1.6					
		0	0.87	0.87	0.87	0.85	0.85	0.85	0.81	0.81	0.81	0.77	0.77	0.77	0.74	0.74	0.74	0.73
		1	0.81	0.78	0.76	0.79	0.77	0.74	0.74	0.72	0.70	0.71	0.69	0.68	0.68	0.67	0.68	0.65
		2	0.75	0.70	0.66	0.73	0.69	0.65	0.66	0.63	0.61	0.64	0.61	0.59	0.62	0.60	0.58	0.57
		3	0.69	0.63	0.59	0.68	0.62	0.57	0.60	0.56	0.52	0.58	0.54	0.52	0.56	0.53	0.51	0.49
		4	0.64	0.56	0.51	0.62	0.55	0.50	0.54	0.49	0.46	0.52	0.48	0.45	0.51	0.47	0.44	0.43
		5	0.59	0.51	0.45	0.58	0.50	0.44	0.48	0.44	0.40	0.47	0.43	0.40	0.46	0.42	0.39	0.38
		6	0.55	0.46	0.40	0.53	0.45	0.40	0.44	0.39	0.35	0.43	0.38	0.35	0.42	0.38	0.35	0.33
		7	0.51	0.42	0.36	0.50	0.41	0.36	0.40	0.35	0.31	0.39	0.35	0.31	0.38	0.34	0.31	0.30
		8	0.47	0.38	0.32	0.46	0.38	0.32	0.37	0.32	0.28	0.36	0.31	0.28	0.35	0.31	0.28	0.27
		9	0.44	0.35	0.29	0.43	0.35	0.29	0.34	0.29	0.25	0.33	0.29	0.25	0.32	0.28	0.25	0.24
		10	0.41	0.32	0.27	0.40	0.32	0.27	0.31	0.26	0.23	0.31	0.26	0.23	0.30	0.26	0.23	0.22

* Include ballast and tilt factors in LLF if appropriate.

TABLE 26-22 Percent Effective Ceiling- or Floor-Cavity Reflectance for Various Reflectance Combinations*

	90				80				70				50				30				10			
	% base reflectance†		% wall reflectance		90		80		70		50		30		10		30		10		30		10	
Cavity ratio	90	70	90	70	90	70	90	70	90	70	90	70	90	70	90	70	90	70	90	70	90	70	90	70
0	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90
0.1	90	89	88	87	90	89	88	87	90	89	88	87	90	89	88	87	90	89	88	87	90	89	88	87
0.2	89	88	86	85	89	88	86	85	89	88	86	85	89	88	86	85	89	88	86	85	89	88	86	85
0.3	89	87	85	83	88	86	84	82	87	85	83	81	86	84	82	80	85	83	81	79	84	82	80	78
0.4	88	86	83	81	88	86	83	81	87	84	81	78	85	82	79	76	83	80	77	74	81	78	75	72
0.5	88	85	81	78	87	84	80	77	86	82	78	74	82	78	74	70	80	76	72	68	77	73	69	65
0.6	88	84	80	76	87	83	79	75	85	81	77	73	81	77	73	69	79	75	71	67	76	72	68	64
0.7	88	83	78	74	86	81	76	72	84	79	74	70	82	77	73	69	80	76	72	68	75	71	67	63
0.8	87	82	77	73	85	80	75	71	83	78	73	69	81	76	72	68	78	74	70	66	73	69	65	61
0.9	87	81	76	71	84	79	74	70	82	77	73	69	81	76	72	68	78	74	70	66	73	69	65	61
1.0	86	80	74	69	83	77	71	66	81	75	69	63	79	73	67	61	80	74	68	62	70	64	58	52
1.1	86	79	73	67	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.2	86	78	72	65	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.3	85	78	70	64	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.4	85	77	69	62	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.5	85	76	68	61	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.6	85	75	66	59	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.7	84	74	65	58	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.8	84	73	64	56	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
1.9	84	73	63	55	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.0	83	72	62	53	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.1	83	71	61	52	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.2	83	70	60	51	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.3	83	69	59	50	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.4	82	68	58	48	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52
2.5	82	68	57	47	83	76	70	64	81	74	68	62	79	72	66	60	80	73	67	61	70	64	58	52

TABLE 26-22 Percent Effective Ceiling- or Floor-Cavity Reflectance for Various Reflectance Combinations* (Continued)

% base reflectance [†]	90				80				70				50				30				10			
	90	70	50	30	80	70	50	30	70	50	30	70	50	30	65	50	30	10	50	30	10			
% wall reflectance																								
2.6	82	67	56	46	66	60	50	41	53	43	35	41	34	26	27	23	18	13	9	5	10			
2.7	82	66	55	45	66	60	49	40	52	43	34	41	33	26	27	23	18	13	9	5	10			
2.8	81	66	54	44	66	59	48	39	52	42	33	41	33	25	27	23	18	13	9	5	10			
2.9	81	65	53	43	65	58	48	38	51	41	33	40	33	25	27	23	17	12	9	5	10			
3.0	81	64	52	42	65	58	47	38	51	40	32	40	32	24	27	22	17	12	8	5	10			
3.1	80	64	51	41	64	57	46	37	50	40	31	40	32	24	27	22	17	12	8	5	10			
3.2	80	63	50	40	64	57	45	36	50	39	30	40	31	23	27	22	16	11	8	5	10			
3.3	80	62	49	39	64	56	44	35	49	39	30	39	31	23	27	22	16	11	8	5	10			
3.4	80	62	48	38	63	56	44	34	49	38	29	39	31	22	27	22	16	11	8	5	10			
3.5	79	61	48	37	63	55	43	33	48	38	29	39	30	22	26	22	16	11	8	5	10			
3.6	79	60	47	36	62	54	42	33	48	37	28	39	30	21	26	21	15	10	8	5	10			
3.7	79	60	46	35	62	54	42	32	48	37	27	38	30	21	26	21	15	10	8	4	10			
3.8	79	59	45	35	62	53	41	31	47	36	27	38	29	21	26	21	15	10	8	4	10			
3.9	78	59	45	34	61	53	40	30	47	36	26	38	29	20	26	21	15	10	8	4	10			
4.0	78	58	44	33	61	52	40	30	46	35	26	38	29	20	26	21	15	9	8	4	10			
4.1	78	57	43	32	60	52	39	29	46	35	25	37	28	20	26	21	14	9	8	4	10			
4.2	78	57	43	32	60	51	39	29	46	34	25	37	28	19	26	20	14	9	8	4	10			
4.3	78	56	42	31	60	51	38	28	45	34	25	37	28	19	26	20	14	9	8	4	10			
4.4	77	56	41	30	59	51	38	28	45	34	24	37	27	19	26	20	14	8	8	4	10			
4.5	77	55	41	30	59	50	37	27	45	33	24	37	27	19	25	20	14	8	8	4	10			
4.6	77	55	40	29	59	50	37	26	44	33	24	36	27	18	25	20	14	8	8	4	10			
4.7	77	54	40	29	58	49	36	26	44	33	23	36	26	18	25	20	13	8	8	4	10			
4.8	76	54	39	28	58	49	36	25	44	32	23	36	26	18	25	19	13	8	8	4	10			
4.9	76	53	38	28	58	49	35	25	44	32	23	36	26	18	25	19	13	7	8	4	10			
5.0	76	53	38	27	57	48	35	25	43	32	22	36	26	17	25	19	13	7	8	4	10			

*Tabular values based on 1:6 length-to-width ratio.

†Ceiling, floor or floor of cavity.

TABLE 26-23 Multiplying Factors for 10% Effective Floor-Cavity Reflectance
(20% = 1.00)

Effective ceiling cavity reflectance, ρ_{sc}	80								70				50				30				10						
	70				50				30				10				50				30				10		
% wall reflectance, ρ_w	70	50	30	10	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10						
Room cavity ratio:																											
1	0.923	0.929	0.935	0.940	0.933	0.939	0.943	0.948	0.956	0.960	0.963	0.973	0.976	0.979	0.989	0.991	0.993	0.995	0.998	0.991	0.993						
2	0.931	0.942	0.950	0.958	0.940	0.949	0.957	0.963	0.962	0.968	0.974	0.976	0.980	0.985	0.988	0.991	0.995	0.996	0.998	0.991	0.995						
3	0.939	0.951	0.961	0.969	0.945	0.957	0.966	0.973	0.967	0.975	0.981	0.978	0.983	0.988	0.992	0.996	0.996	0.996	0.998	0.992	0.996						
4	0.944	0.958	0.969	0.978	0.950	0.963	0.973	0.980	0.972	0.980	0.986	0.980	0.986	0.991	0.987	0.992	0.996	0.996	0.998	0.992	0.996						
5	0.949	0.964	0.976	0.983	0.954	0.968	0.978	0.985	0.975	0.983	0.989	0.981	0.988	0.993	0.987	0.992	0.997	0.997	0.998	0.992	0.997						
6	0.953	0.969	0.980	0.986	0.958	0.972	0.982	0.989	0.977	0.985	0.992	0.982	0.989	0.995	0.987	0.993	0.997	0.997	0.998	0.993	0.997						
7	0.957	0.973	0.983	0.991	0.961	0.975	0.985	0.991	0.979	0.987	0.994	0.983	0.990	0.996	0.987	0.993	0.998	0.998	0.993	0.998	0.998						
8	0.960	0.976	0.986	0.993	0.963	0.977	0.987	0.993	0.981	0.988	0.995	0.984	0.991	0.997	0.987	0.994	0.998	0.998	0.994	0.998	0.998						
9	0.963	0.978	0.989	0.994	0.965	0.979	0.989	0.994	0.983	0.990	0.996	0.985	0.992	0.998	0.988	0.994	0.999	0.999	0.994	0.999	0.999						
10	0.965	0.980	0.989	0.995	0.967	0.981	0.990	0.995	0.987	0.991	0.997	0.986	0.993	0.998	0.988	0.994	0.999	0.999	0.994	0.999	0.999						

TABLE 26-24 Multiplying Factors for 30% Effective Floor-Cavity Reflectance
(20% = 1.00)

% effective ceiling cavity reflectance, ρ_{cc}	80						70						50						30						10					
	70			50			30			10			50			30			10			50			30			10		
	% wall reflectance, ρ_w																													
Room cavity ratio:	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	50	30	10	
1	1.092	1.082	1.075	1.068	1.077	1.070	1.064	1.059	1.049	1.044	1.040	1.028	1.026	1.021	1.017	1.026	1.021	1.017	1.023	1.012	1.010	1.012	1.010	1.008	1.008	1.006	1.005	1.004	1.003	
2	1.079	1.066	1.055	1.047	1.068	1.057	1.048	1.039	1.041	1.033	1.027	1.020	1.024	1.017	1.012	1.024	1.017	1.012	1.017	1.012	1.010	1.012	1.010	1.008	1.006	1.005	1.004	1.003	1.002	
3	1.070	1.054	1.042	1.033	1.061	1.048	1.037	1.028	1.034	1.027	1.020	1.024	1.017	1.012	1.017	1.010	1.005	1.010	1.017	1.012	1.010	1.012	1.010	1.008	1.006	1.005	1.004	1.003	1.002	
4	1.062	1.045	1.033	1.024	1.055	1.040	1.029	1.021	1.030	1.022	1.015	1.022	1.015	1.012	1.017	1.010	1.005	1.010	1.017	1.012	1.010	1.012	1.010	1.008	1.006	1.005	1.004	1.003	1.002	
5	1.056	1.038	1.026	1.018	1.050	1.034	1.024	1.015	1.027	1.018	1.012	1.020	1.013	1.008	1.015	1.008	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	
6	1.062	1.033	1.021	1.014	1.047	1.030	1.020	1.012	1.024	1.015	1.009	1.019	1.012	1.006	1.014	1.008	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	
7	1.047	1.029	1.018	1.011	1.043	1.026	1.017	1.009	1.022	1.013	1.007	1.018	1.010	1.005	1.014	1.008	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	
8	1.044	1.026	1.015	1.009	1.040	1.024	1.015	1.007	1.020	1.012	1.006	1.017	1.009	1.004	1.013	1.007	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	
9	1.040	1.024	1.014	1.007	1.037	1.022	1.014	1.006	1.019	1.011	1.005	1.016	1.009	1.004	1.013	1.007	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	
10	1.037	1.022	1.012	1.006	1.034	1.020	1.012	1.005	1.017	1.010	1.004	1.015	1.009	1.003	1.013	1.007	1.003	1.008	1.015	1.010	1.008	1.010	1.008	1.006	1.004	1.003	1.002	1.002	1.002	

luminaires required. For direct and semidirect luminaires, spacing between columns and rows should not exceed the maximum spacing as determined by the spacing criterion values for the luminaire.

Example. A room is 28 ft wide and 32 ft long and has a 10-ft ceiling height.

Reflectances are: ceiling 80%, walls 50%, floor 10%. A recessed four-lamp fluorescent luminaire is to be used. Work plane is 2 ft 0 in. Find the coefficient of utilization.

1. In Table 26-21, lookup *effective cavity reflectances* for ceiling and floor cavities. *pcc* for the ceiling cavity will be 80%, while *pfc* for the floor cavity will be 11%.
2. With the room-cavity ratio RCR known, it is now possible to find the coefficient of utilization for the luminaire in a room having an RCR of 2.7 and effective reflectances as follows (assume luminaire is type described in Table 26-21):

$$pcc = 80\% \quad pw = 50\% \quad pfc = 20\%$$

Thus CU = 0.65. Note that this is for an effective floor reflectance of 20%, while the actual effective reflectance of the floor *pfc* is 11%. To correct for this, locate the appropriate multiplier in Table 26-24 for the RCR already calculated (2.7). It is 0.948 and is found by interpolating between the numbers for 80 *pcc* and between RCRs of 2.0 and 3.0. Then

$$CU_{\text{final}} = 0.65 \times 0.948 \times 0.62$$

The average illuminance across the space can now be calculated if we know the lamp lumen rating, and the light-loss factor.

$$E_{\text{ave}} = \frac{(\text{number of luminaires}) \times (\text{rated lamp lumens / luminaire}) \times CU \times LLF}{\text{room area}}$$

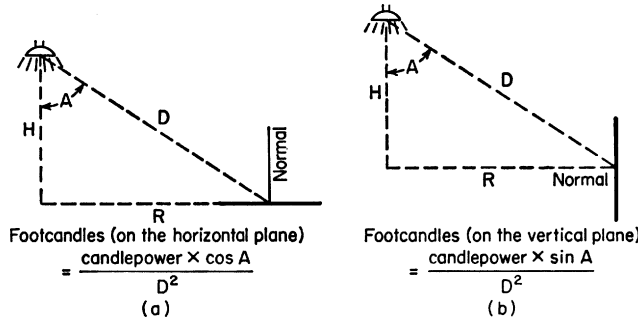
Simplified Design Methods. Buildings may have many individual spaces of different dimensions. If all of the above steps were used to determine the number of luminaires (and/or the number of lamps per luminaire) for each space, the procedure might be too time-consuming or unnecessary accurate or both. Engineers may wish, therefore, to use simplified performance data provided by the luminaire manufacturer in technical portions of catalogs, etc.

One popular method is based on specific illuminance levels for a small group of room proportions (ratios of room width to room or mounting height), and for assumed room-surface reflectances. By using typical light-loss factors, the approximate square footage per luminaire can be calculated using the formula under item 6 of the basic steps in calculating average illuminance.

26.13 CALCULATION OF ILLUMINANCE AT A POINT

Point Calculation Methods. The calculation of the illuminance at a point, whether on a horizontal, a vertical, or an inclined plane consists of two parts—the direct component and the reflected component. The total of these two components is the illuminance at the point in question.

Direct Component Illuminance. Most methods are based on the application of the *inverse-square law* ($E = I/D^2$, where I equals the luminous intensity expressed in candelas obtained from the candlepower distribution curve for the luminaire). In applying this formula to a horizontal surface, the illuminance at any point P is equal to the candlepower directed toward P multiplied by the cosine of the angle A and divided by the square of the distance D from the luminaire [$E = (I \times \cos A)/D^2$]. In this case A is the angle between the axis of the luminaire and a line from the light center to point P .



Reflected Component Illuminance. The reflected component consists of light that strikes the work plane, or any other point of interest after reflection from one or more of the room surfaces. In direct lighting systems and large rooms, this component may be small (less than 20% of the total illuminance at a point), while for indirect lighting systems, all of the light striking the work plane may be reflected. Illuminance calculated with the lumen method includes both the average direct and reflected illuminance on the work plane. For more detailed point-by-point calculations, advanced computer software often apply algorithms that subdivide the room surfaces into smaller patches for analysis of the reflected contribution, providing grids of points at which the illuminance is computed due to both direct and reflected light. Many of these computer programs also provide renderings of how an architectural space might appear. These tools are useful for analyzing lighting systems that do not provide uniform illuminance over the entire space, or to address conditions over a specific area or task location. A survey of lighting software is regularly published in the IESNA's periodical *Lighting Design + Application*.¹

REFERENCE ON LIGHTING CALCULATIONS

1. Rea, M.S., Ed., *IES Lighting Handbook*, Chapter 9. IESNA 2000.

26.14 FLOODLIGHTING DESIGN AND PROCEDURE

Beam-Lumen Method. All floodlighting-design methods include certain approximations, based on experience. In floodlighting systems containing a large number of luminaires, a detailed computer study of point source calculations with luminaire locations and aiming positions is usually required. A procedure which is useful for designing simpler systems is called the "beam-lumen" method. This method requires the solution of the two formulas (A and B), as discussed in the following paragraphs, and the coordination of the results.

In many locations in which floodlighting is proposed, there are some basic dimensions that can be assumed to be already fixed. For example, in ground-area floodlighting, the designer is usually able to locate points where the equipment should logically be placed, such as on poles/towers or other physical structures. These locations establish the approximate perpendicular distance D from the floodlight to the plane of the surface to be lighted and the average aiming angles. They also guide the choice of floodlight type—narrow, medium, or broad-beam. In like manner the choice of equipment for lighting vertical surfaces can be obtained by taking D as the horizontal distance from the luminaire to the plane in which the vertical surface is located.

The average aiming angle is measured from the perpendicular to the beam-axis line (Fig. 26-37). In a perimeter system in which the floodlights are mounted along or beyond the perimeter of an area, they will, of course, be aimed at various angles, but the average aiming angle used in computation is

measured between the perpendicular and the centerline of the area to be lighted. When floodlights are on poles along the centerline of an area, the average aiming angle is measured between the pole (perpendicular) and a point halfway to the boundary (one-fourth of the width of the total area).

Design Formulas and Procedure

$$\text{Formula A} = \frac{(\text{area lighted}) \times (\text{coverage factor})}{\text{floodlights needed for coverage} \times \text{beam - spot area}}$$

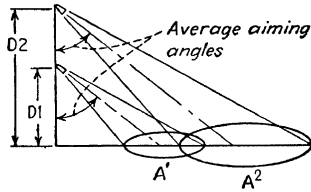


FIGURE 26-37 Spot areas (for the same beam spread and aiming angle) vary as the square of the distance D . Spot length L and spot width W vary as the distance D . The spot area may be determined from $\pi LW/4$.

In this formula, the area to be lighted may be either a horizontal surface or a vertical one.

The coverage factor indicates the minimum number of directions from which each point in the area should be lighted, depending on the use of the area. A coverage factor of 1 is acceptable in some applications, although in such systems one or two lamp burnouts might temporarily leave large dark patches. Coverage factors greater than 1 therefore add desirable safety factors. For example, a coverage factor of 2 is necessary for parking spaces and for protective lighting to reduce the effect of shadows between automobiles, rows of freight cars, piles of material, and similar bulky objects (see Table 26-25 for other recommended values).

The beam-spot areas at a (100-ft) distance D in formula A are given in Table 26-25 for various beam spreads and aiming angles of usual equipment having symmetrical candlepower distribution. In this table, D is the perpendicular distance measured from the floodlight to the plane of the lighted surface. L and W are the lengths and widths of the ellipses formed when floodlights are aimed at an angle to the lighted surface. At 0° the area is assumed to be circular; at other angles, it is elliptical. At other distances and spreads and for similar beam spreads and aiming angles, the spot areas vary as the square of the distance D , while L and W vary as the distance D . For example, if D is (24.38 m / 80 ft) and a 30 beam-spread floodlighting unit is aimed at a 50° angle, the elliptical spot areas computed from Table 26-22 will be $(80)^2/(100)^2 \times 9978$, or 6386 ft². Likewise, the length L of the ellipse will be $80/100 \times 144.4$, or 115.5 ft, and the width W will be $80/100 \times 87.96 = 70.4$ ft.

Formula B:

$$\text{Number of floodlights needed} = \frac{\text{illuminance} \times \text{area lighted}}{\text{light - loss factor} \times \text{utilization factor} \times \text{beam lumens}}$$

The light-loss factor allows for dust, dirt, and normal lamp depreciation. This is found under average conditions to be about 0.7. However, it may be as low as 0.3 for extremely dirty locations, where dust, dirt, and smoke are frequently suspended in the air.

The utilization factor, or coefficient of beam utilization, is the ratio of the lumens effectively lighting an area to the beam lumens, and it can be estimated from the following conditions:

1. If half or more than half of the floodlights are aimed so that all their beam lumens fall within an area, the overall utilization factor will be about 0.75.
2. If one-quarter to one-half of the floodlights are aimed so that all their beam lumens fall within an area, the overall utilization factor will be about 0.60.
3. If fewer than one-quarter of the floodlights can be aimed so that their beam lumens fall within an area, the overall utilization factor is likely to be not more than 0.40.

Most floodlights and projector- and reflector-type lamps as listed in the manufacturer's catalog are rated in beam lumens. These lumen ratings usually include only the light flux in that part of the

TABLE 26-25 Typical Recommended Illuminance Levels for Floodlighting, with Recommended Coverage Factors

Area	Footcandles	Lux	Minimum coverage factor
Building			3–4
General construction	10	100	
Excavation work	2	20	
Building exteriors and monuments:			2
Floodlighted			
Bright surroundings			
Light surfaces	5	50	
Medium-light surfaces	7	70	
Medium-dark surfaces	10	100	
Dark surfaces	15	150	
Dark surroundings			
Light surfaces	2	20	
Medium-light surfaces	3	30	
Medium-dark surfaces	4	40	
Dark surfaces	5	50	
Bulletin and poster boards:			1–2
Bright surroundings			
Light surfaces	50	500	
Dark surfaces	100	1000	
Dark surroundings			
Light surfaces	20	200	
Dark surfaces	50	500	
Open parking facilities*			
Basic	1	10	
Enhanced security	2.5	25	
Covered parking facilities			
General parking and pedestrian areas			
Day	5 [‡]	50 [‡]	
Night	5 [†]	50 [†]	
Ramps and corners			
Day	2	20	
Night	1	10	
Entrance areas			
Day	50 [‡]	500 [‡]	
Night	1	10	
Service station (at grade)			3–4
Dark surrounding			
Approach	1.5	15	
Driveway	1.5	15	
Pump— island area	5	50	
Building faces (exclusive of glass)	2	20	
Service areas	2	20	
Light surrounding			
Approach	2	20	
Driveway	2	20	
Pump— island area	10	100	
Building faces (exclusive of glass)	3	30	
Service areas	3	30	

*Based on recommended illuminance for pedestrian safety, Uniformity ratio 5:1.

†Minimum on pavement.

‡Minimum on pavement, sum of electric lighting and daylight.

§Vertical.

beam in which the candlepower values are 10% or more of the maximum candlepower of the floodlight.

As a general rule, it is wiser to design a system with a small number of floodlights with larger, more efficient lamps. This makes a simpler system to install, to control, and to maintain. Also from a control-of-light point of view it is desirable to choose a floodlighting unit having as narrow a beam spread as can be used and still maintain the coverage-factor requirements. It should be remembered, however, that large floodlights are hard to conceal; this is important where their daytime appearance may be objectionable architecturally.

To solve formula B, after choosing the desired illuminance and determining the light-loss and utilization factors, a size of floodlight is chosen for trial calculation and its beam lumens are substituted in the equation.

When the dimensions or shape of an area lead to the use of several types of floodlights, with different beam spreads, it is customary to divide the area into sections and plan a system for each of them. Buildings with setbacks are typical examples, also very tall structures such as towers or monuments. In setback buildings, you would design one setback at a time, selecting the type of floodlight most suitable for each. With towers or monuments, a similar approach is in order.

Floodlighting Design Problem. Assume that an area 200 by 200 ft is to be lighted to 5 fc. Also assume that the floodlights will be mounted on poles that are 60 ft high located on opposite sides of this area. By using a scale drawing to represent the luminaires placed 60 ft high and aimed toward the center line of the 200-ft-wide work space, the aiming angle will be about 60°. For trial-computation purposes it is best to start with the assumption that a narrow-beam-spread floodlighting unit will serve the coverage requirements and then change to a wider beam if found desirable. Hence, for this work space the lighting-design procedure is as follows:

1. From Table 26-26 the area which can be lighted for a 15° floodlight mounted 60 ft high at an aiming angle of 60° is

$$\frac{(60)^2}{(100)^2} \times 4720 = 1700 \text{ ft}^2$$

TABLE 26-26 Spot Areas for Narrow-, Medium-, and Broad-Beam Floodlights at a 100-ft Distance*

Aiming angle	15-deg beam, narrow			30-deg beam, medium			50-deg beam, broad		
	Spot area	L	W	Spot area	L	W	Spot area	L	W
0	545	26.34	26.34	2,250	53.58	53.58	6,830	93.26	93.26
10	570	27.16	26.70	2,370	55.38	54.49	7,220	96.81	95.00
15	606	28.25	27.30	2,518	57.70	55.56	7,760	101.54	97.30
20	657	29.89	28.00	2,757	61.27	57.29	8,600	108.75	100.7
25	735	32.18	29.1	3,102	66.28	59.58	9,880	119.18	105.5
30	846	35.31	30.5	3,603	73.21	62.67	11,770	134.06	111.8
35	1,000	39.57	32.3	4,333	82.78	66.64	14,710	155.58	120.4
40	1,230	45.42	34.6	5,420	96.18	71.75	19,500	187.66	132.3
45	1,583	53.59	37.6	7,129	115.46	78.62	27,900	238.35	149.0
50	2,115	65.34	41.3	9,978	144.43	87.96	44,810	326.58	174.7
55	3,043	82.97	46.7	15,160	190.84	101.14	87,140	509.39	217.8
60	4,720	111.10	54.1	25,880	273.21	120.6	265,100	1072.99	314.6
65	8,165	160.19	64.9	54,480	447.94	154.85			
70	16,800	258.97	82.6	180,910	1000.2	230.3			

*The spot area for any other distance can be computed by multiplying the area in this table at the selected aiming angle by D^2 and dividing by 10,000.

2. Solving formula A

$$\text{No. of } 15^\circ \text{ units needed for coverage} = \frac{(\text{area}) \times (\text{coverage factor})}{\text{spot area}} = \frac{40,000 \times 3}{1700} = 70$$

3. Solving formula B. A light-loss factor of 0.3 is found for this dirty location, and a utilization factor of 0.7 may be assumed for narrow-beam floodlights in this area. If a 1000-W incandescent unit is selected for a trial computation, and it has 9500 beam lm. Then the number of 1000-W floodlights needed =

$$\begin{aligned} \text{1000-W floodlights needed} &= \frac{(\text{illuminance}) \times (\text{area})}{\text{LLF} \times \text{UF} \times \text{beam lumens}} \\ &= \frac{5 \times 40,000}{0.3 \times 0.7 \times 9500} = 100 \end{aligned}$$

4. Since the number of floodlights (100) in formula B is greater than the number needed for adequate coverage, it could be concluded that, if 50 floodlight units are conveniently located on either side of the area, a satisfactory 5-fc lighting installation would be provided. On the other hand, if a minimum number of floodlights are desired, formula B can be resolved on the basis of using 1500-W luminaires having 12,300 beam lm. In this case,

$$\text{1500-W floodlights needed} = \frac{5 \times 40,000}{0.3 \times 0.7 \times 12,300} = 77$$

Hence, this work area can be satisfactorily lighted with 5 fc maintained in serviced if thirty-nine 1500-W 15° floodlights are well distributed along each side of the area at 60-ft mounting heights.

As seen from the foregoing example, it is possible to use a fewer number of higher-wattage luminaires when the number of units (formula B) to provide the required illuminance is considerably greater than the number required for adequate coverage (formula A). On the other hand, when the trial computations show that the number of luminaires to provide the required illuminance is less than those for adequate coverage, it becomes necessary to recalculate formula B by using beam lumens from smaller-sized units, until one is found which brings the answer equal to or greater than that for formula A. In other words, the answer to formula B should preferably never be less than that for formula A in order to provide adequate illumination as well as satisfactory coverage. In all cases, consideration should be given to the use of lamps with the highest luminous efficacy of a color suitable for the application if HID floodlights of appropriate beam spreads are available.

A more detailed point-by-point floodlighting design could also be computed using software. In any floodlighting installation, care should be taken to avoid light trespass and light pollution (light directed to the sky). Local outdoor lighting ordinances may restrict illuminance levels or the use of particular types or mounting heights of outdoor lighting equipment.

26.15 ECONOMICS OF LIGHTING

The Value of Lighting. The value of good lighting depends on its use in the various fields of application.

Reports from a variety of industrial plants have indicated that better lighting created more satisfactory working conditions which in many instances meant an increase in production, reduced, spoilage, fewer accidents, and less labor turnover. Likewise, in stores and other selling areas, good lighting properly applied has been recognized as a necessity, not only to permit the customer to properly inspect the

merchandise but also to direct his or her attention to displayed items and thereby increase the volume of sales. Moreover, light and lighting are an integral part of many modern buildings where the architect has incorporated luminous elements for their functional use and aesthetic value.

Reduced office productivity can be caused by poor lighting. In addition, workers using computers can experience headaches, eye strains, and other ergonomics-related problems from improper lighting.

For utilitarian installations, which have resulted in an increase in factory production or an increase in sales in a store, a dollars-and-cents value can readily be given to better lighting, but this is rarely something that can be predicted prior to system installation. On the other hand, there is wide acceptance of light and lighting for its humanitarian and decorative aspects, which are of inestimable value.

Cost of Lighting. The overall items for comparing different lighting systems must include both the initial and the operating cost. While one of these may be a dominant factor in the final selection, it is usually desirable to combine the two into some type of “total cost” indicator.

The computation of initial, operating, and total annual cost for various systems considered for a given interior must be based on certain common assumptions, if the systems are to be fairly compared. Some of the important considerations are:

1. Equal illuminance results—since different systems may not produce equal illumination levels in service, all costs should be equated to an equal maintained illuminance basis.
2. Equal rates for amortizing the initial investment and for addressing interest, taxes, and insurance should be used.
3. Equivalent electrical-energy rates and operating conditions (burning hours per year and starting frequency of the lamps) should be applied to different systems.
4. Cleaning schedule should be appropriate to each type of system.
5. Uniform labor rates among systems should be used for estimating the cost of installations, cleaning, and relamping. Some users request life-cycle costs.

Table 26-27 tabulates a cost-analysis procedure for comparing the cost of two or more lighting systems and is self-explanatory. Table 26-27 develops capital expense based on initial costs divided by the assumed year's life, and operating expenses computed from present energy, lamp replacement, cleaning, and repair costs. A simple payback analysis may also be computed from the differential first cost between two systems and the annual savings that a system provides. Life cycle costing is preferred by many owners, because it considers the present value of money, which depends on the rate of interest, and provides the most accurate measure of economic performance (see IESNA publication RP-31-96, *Economic Analysis of Lighting*).

Group-Relamping Costs. The cost of lamp replacement is made up of the cost of the lamp and the cost of labor required to replace the lamp. When the sum of the costs is reduced, of course, the total annual cost of operating the lighting system is reduced. It is difficult to assess the exact overall cost reduction without having all the other facts about the installation, but it should be kept in mind that economical lamp replacement means better overall lighting economics.

With spot replacement, the total replacement cost per lamp is equal to the cost of the lamp plus the labor cost of replacement. Group-relamping cost, to compare with this, is equal to the lamp cost plus group-relamping labor cost plus the cost of any interim spot replacements, divided by the group relamping interval to put both systems on an equal time basis.

REFERENCE ON ECONOMICS OF LIGHTING

1. *Economic Analysis of Lighting*, RP 31-96. IESNA 1996.

TABLE 26-27 Cost-Analysis Outline for Lighting Systems

General information	Lighting system 1	Lighting system 2
Installation data	...	...
Type of installation	...	...
Number of rows	...	...
Luminaires per row	...	...
Lamps per luminaire	...	...
Number of lamps	...	...
Watts per luminaire (including accessories)	...	...
Total watts	...	...
Maintained illuminance	...	...
Calculation of complete expense		
Capital expense	...	...
Estimated cost of each luminaire installed	...	...
Estimated wiring cost per luminaire	...	...
Cost per luminaire (luminaire plus wiring)	...	...
Number of luminaires	...	...
Total cost	...	...
Assumed years life	...	...
Total cost per year of life	...	...
Interest on investment (per year)	...	...
Taxes (per year)	...	...
Insurance (per year)	...	...
Total capital expense per year	...	...
Energy expense	...	...
Total watts	...	...
Average hours used per year	...	...
kWh per year	...	...
Average rate per kWh	...	...
Total energy expense per year	...	...
Lamp-renewal expense:	...	...
Number of lamps	...	...
Hours used per year	...	...
Total lamp hours per year	...	...
Rated lamp life, h	...	...
Average lamp renewals per year	...	...
Net price each	...	...
Replacement expense each (labor)	...	...
Net price plus replacement expense each	...	...
Total lamp-renewal expense per year	...	...
Lighting	Lighting	Lighting
Calculation of complete expense	system 1	system 2
Cleaning expense	...	...
Number of washings per year	...	...
Worker-hours each (est.)	...	...
Worker-hours for washing	...	...
Number of dustings per year	...	...
Worker-hours each (est.)	...	...
Worker-hours of dusting	...	...
Total worker-hours	...	...

TABLE 26-27 Cost-Analysis Outline for Lighting Systems (*Continued*)

Lighting Calculation of complete expense	Lighting system 1	Lighting system 2
Expense per worker-hour	...	...
Total cleaning expense per year	...	...
Repair expense	...	...
Repairs (based on experience, allocation of repair worker's time, etc.)	...	...
Estimate of total repair expense per year	...	...
Lamp disposal expense per year*	...	...
General information		
Recapitulation	...	...
Total capital expense per year	...	...
Total energy expense per year	...	...
Total lamp renewal expense per year	...	...
Total cleaning expense per year	...	...
Estimate of total repair expense per year	...	...
Estimate of total lamp disposal expense per year	...	...
Complete lighting expense for year	...	...

*An essential ingredient of fluorescent and HID lamps is a small amount of mercury. More strict regulations now apply to the disposal of such lamps, to minimize the possibility of contaminating air and water.

26.16 LIGHTING MAINTENANCE

Maintenance of Lighting. Good lighting system maintenance is good economics, that is, good maintenance assures users that they actually get the light they pay for. With a well-maintained lighting system, the user also gets the better conditions that the system was designed to provide. These better seeing conditions contribute directly to higher productivity and improved morale in factories, offices, and schools. In stores, the better lighting that results from good maintenance helps to increase sales. In addition, all areas benefit from a better appearance and fewer work interruptions that come with good maintenance.

Causes of Light Loss. Several factors contribute to light loss, and the effects of these factors vary with the kind of activity that takes place and the location of the establishment. For example, spaces vary as to the amount and type of dirt present in the air. Obviously, the amount of dirt in a machining factory is greater than that in an air-conditioned office. It is important to recognize these variations in considering the light losses which result from dirt on lamps and lighting units and dirt on room surfaces. These two, along with the unavoidable lamp-lumen depreciation, are the principal factors that cause light loss in every lighting installation.

Benefits of Cleaning. A lighting system should not only be cleaned properly, it should be cleaned at the proper time. This combination produces a cleaning program, which is a profitable investment because three principal benefits can be obtained.

1. *Better energy utilization for lighting.* Dirt absorbs light—cleaning removes the dirt and thus helps to maintain the light level. As a result, visibility is maintained, which benefits the user.
2. *Reduced maintenance costs.* A good maintenance program calls for cleaning the lighting system at the most economical time. It makes use of the most efficient methods and equipment. In this way the time and materials required are reduced, thus maintenance costs are lowered.

3. *Better appearance.* Clean lighting systems improve the appearance of the space. This is conducive to improved morale, better housekeeping, and increased occupant satisfaction.

To further improve the appearance of the area being lighted, walls and ceilings should be periodically cleaned and repainted as part of the cleaning program.

Relamping Benefits. The lamps in a lighting system can be replaced individually as they burn out, or the entire installation can be replaced before the lamps reach their average life. Individual replacement is usually called *spot replacement*; mass replacement is called *group relamping*. The labor costs saved by group relamping in large installations and in many small ones more than compensate for the value of the depreciated lamps that are thrown away before they burn out. Other advantages which always accompany group relamping are more light, fewer work interruptions, better appearance of the lighting system, and less maintenance of auxiliary equipment.

There are five principal advantages for group relamping. The first three apply to all lighting systems, the last two chiefly to fluorescent and HID systems.

1. *Reduced labor costs often mean net savings.* Group relamping saves on labor costs, largely because much of the travel and setup time required to change lamps individually is eliminated.
2. *More light delivered.* All lamps depreciate in lumens continually as they burn. The earlier they are replaced, the higher the maintained illumination will be without adding to the use and cost of electric energy since a larger number of luminaires are needed to achieve a target design illuminance.
3. *Fewer work interruptions.* Group relamping can be done at a convenient time—during vacation shutdowns or after working hours, for example, when there will be no interruption of operations. The number of interruptions to report burnouts or to replace them is greatly reduced.
4. *Better appearance of the lighting system.* Black ends, color variations, and differences in brightness between adjacent old and new fluorescent lamps are common when spot replacement is used. With group relamping, all the lamps are the same age, and appearance is more uniform.
5. *Less maintenance of auxiliary equipment.* Abnormal operating conditions that may occur at the end of lamp life can damage starters and ballasts. When most of the lamps are replaced before they reach the end of life, auxiliary equipment lasts longer.

26.17 LIGHTING MEASUREMENT DEVICES

A variety of light measurement devices are available to a lighting practitioner for use in measuring lighting system performance. The most common devices are meters to measure illuminance and luminance.

Illuminance Meter. An illuminance meter is generally constructed with a silicon or selenium cell placed beneath an integrating white diffuser that may be either flat or round. The cells generate a potential difference when irradiated which bears a relationship to the level of illumination. The cells also have a spectral sensitivity that is chiefly in the visible and near ultraviolet region. Because it is different than that of the human eye, to measure photometric quantities (quantities based on the definition of the lumen) the cell must contain a color-correcting filter to align the detector's performance with that of the CIE luminous efficiency curve (see Fig. 26-38). Illuminance meters must also provide a reading that follows the cosine law of illuminance. That is, that the illuminance is proportional to the cosine of the angle the incident light ray makes with the normal to the measurement surface. Most illuminance meters perform well in this regard, but are less accurate at very high incident light angles (above 75° to 80°). When using an illuminance meter, it is important to properly orient the meter and to avoid shadowing the light arriving at the meter.

Luminance Meter. A luminance meter is used to measure the light leaving a surface in a particular direction. This type of meter must also be color corrected, and is used to record the luminous

intensity (candelas) per projected area leaving the surface in the direction of the meter. Luminance meters are typically configured with a lensed optical system and an eyepiece through which the operator views the surface. A circle in the center of the image viewed through the meter indicates the surface area to be measured. The angular extents of this measurement zone may vary, but it is typically on the order of 1° or some fraction of a degree. When using a luminance meter, it is important that the operator focus the image using an adjustable outer lens. Since it may be difficult to hold such a meter steady and achieve a static reading, these meters typically have a trigger that may be pulled to make a reading, then released to freeze the reading.

Other more specialized devices for measuring lighting quantities are also available. These are unlikely to be needed by a lighting designer, but may be useful to manufacturers, research laboratories, and other lighting specialists. This list of devices include chromaticity meters, exposure meters, reflectometers, goniophotometers, glossmeters, fluorometers, colorimeters, refractometers, and pyranometers.

References on illumination may be found in texts on the subject of illuminating engineering and in appropriate journals. A few are listed in the bibliography.

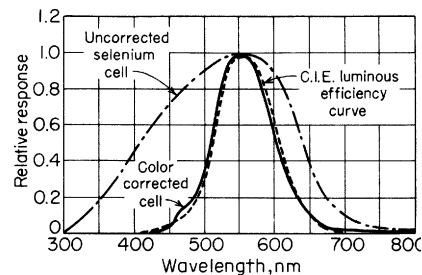


FIGURE 26-38 Average spectral sensitivity characteristics of selenium barrier-layer cells, compared with CIE spectral luminous efficiency curve.

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[†]Formerly, *Illuminating Engineering*, *Transactions of the Illuminating Engineering Society*, and the *Journal of the Illuminating Engineering Society*.